AD-A054 309 CONSTRUCTION ENGINEERING RESEARCH LAB (ARMY) CHAMPAI--ETC F/G 1/5
RELIABILITY ANALYSIS FOR AIRFIELD LIGHTING SYSTEMS.(U)
MAR 78 E S LINDOW, F KUO DOT-FA66WAI-118
UNCLASSIFIED CERL-TR-M-237 FAA-RD-77-148 NL

1 OF 2
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REPORT NO: FAA-RD-77-148

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RELIABILITY ANALYSIS FOR AIRFIELD LIGHTING SYSTEMS

E. S. LINDOW
F. KUO

MARCH 1978

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Prepared for

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
Systems Research & Development Service
Washington, D.C. 20590

NOTICE

Technical Report Documentation Page

(19)

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
(18) FAA-RD-77-148		(11)

4. Title and Subtitle
(6) Reliability Analysis for Airfield Lighting Systems.

5. Report Date
March 1978

6. Performing Organization Code

7. Author(s)
(10) E. S. Lindow and F. Kuo

8. Performing Organization Report No.
(14) CERL-TR-M-237

9. Performing Organization Name and Address
CONSTRUCTION ENGINEERING RESEARCH LABORATORY
P.O. Box 4005
Champaign, IL 61820

10. Work Unit No. (TRAIS)

11. Contract or Grant No.
(15) DOT-FA66WAI-118 new

12. Sponsoring Agency Name and Address
U.S. Department of Transportation
Federal Aviation Administration
Systems Research & Development Service
Washington, DC 20590

13. Type of Report and Period Covered
(9) Final Report.

14. Sponsoring Agency Code

15. Supplementary Notes
(12) 122p.

16. Abstract

This report presents a model for performing reliability analyses of airfield lighting systems. A set of consecutive coefficients was developed to account for system failure criteria which include random light outages, consecutive light outages, and consecutive light bar failures. Probability theory and simulation techniques are used with the consecutive coefficients to determine system reliability. A computerized version of the model was used in a sensitivity analysis to determine the effect on system reliability of parameters such as unit reliability, system configuration, maintenance strategy, and unit performance characteristics.

17. Key Words
Airfield Lighting Systems
Model
Consecutive Coefficients
Reliability Analysis
Sensitivity Analysis

18. Distribution Statement
Document is available to the public through the National Technical Information Service, Springfield, Virginia 22151

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	123	

Form DOT F 1700.7 (8-72)   Reproduction of completed page authorized

405 279   LB

FOREWORD

This research was conducted for the Federal Aviation Administration, Visual Aids Section (FAA-ARD) under Inter Agency Agreement No. DOT-FA66WAI-118. Mr. Walter C. Fisher, Chief, FAA-ARD, was the Technical Monitor, followed on his retirement by Mr. John Simeroth.

The work was performed by the Engineering and Materials Division (EM), of the U.S. Army Construction Engineering Research Laboratory (CERL), Champaign, IL. Appreciation is extended to Mr. J. J. Brown of FOM for his aid in the computer analyses.

Dr. G. R. Williamson is Chief of EM. COL J. E. Hays is Commander and Director of CERL and Dr. L. R. Shaffer is Deputy Director.

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RELIABILITY ANALYSIS FOR AIRFIELD LIGHTING SYSTEMS

1 INTRODUCTION

Background

Visual guidance lighting systems for airports provide necessary information for aircraft operation during approach, landing, take-off, and ground movement (taxiing). In darkness, inclement weather, or other periods of low visibility, the information provided by these systems is critical to safe and efficient air travel. At many major airports, periods of low visibility are encountered during nearly one-half of the operating time.

Although significant research has been devoted to improving component equipment in these lighting systems and to delineating the pilot's information requirements, little has been done to determine the operational reliability of the lighting systems currently in use. Because these systems are critical to safe ard efficient operations and because installation and maintenance costs for such systems are high, procedures to analyze the reliability of present airfield lighting systems are needed.

Purpose

The purpose of this research was to develop procedures for evaluating the functional reliability of airfield lighting systems. The procedures developed here can be used to estimate steady-state system reliability for any visual guidance lighting system.

Approach

A three-step approach was used in this research: development of the methodology, development of the model, and testing of the model.

The methodology for evaluating the reliability of airfield lighting systems was developed through reviewing the literature concerning airfield lighting and systems analysis of reliability. In addition, personnel from the Federal Aviation Administration (FAA), equipment manufacturers, and various airports were contacted.

The second step produced a general lighting system model which, through user selection of input, can be used to evaluate the reliability of individual lighting systems. This model was then automated to provide a simple and efficient procedure for performing these analyses.

Finally, the model was tested through a sensitivity analysis of the several variables influencing system reliability. In addition, a limited field examination of in-service lighting systems was undertaken.

Scope

Due to the complexity of the problem, the number of lighting systems in use, and the variety of components within each system, limitations were placed on the scope of this project. In defining the scope, the following assumptions were made:

a. The functional design of individual items of equipment and systems is adequate. Thus, in defining system reliability, no attempt was made to warrant the system geometry or component characteristics.

b. The operational characteristics of each system are adequate. The standards selected for failure criteria were those presently accepted, and no inference was made as to the level of information conveyance and pilot perception for individual lighting systems.

c. Deviations from standard lighting systems and maintenance practices will be treated through user selection of input variables.

Organization of Report

To simplify use of this report, the body of the report summarizes the study findings, which are documented in detail in the appendices. Appendix A discusses the modeling of visual guidance lighting systems. The reliability methodology used is described in Appendix B. Appendix C presents the derivation of the consecutive coefficient introduced to account for failure criteria stipulating the consecutive outages allowed in a lighting system. Appendix D is the user's manual for the automated program for evaluating system reliability, including an example problem. Appendix E details the sensitivity analysis of the model.

2 AIRFIELD LIGHTING SYSTEM RELIABILITY

Airfield Lighting

Appendix A describes lighting systems which provide pilots with visual guidance during poor visibility conditions. The references listed in the bibliography provide additional information on the individual systems.

Although each system is comprised of specialized equipment in configurations designed to convey the necessary information to pilots, they all have the common elements of a power source, power circuitry, and light transmission equipment. Because of these similarities, a general model can be used to define all the lighting systems.

The General Lighting System Model

The model used to define airfield lighting systems (Figure 1) consists of 12 components: commercial power, auxiliary power, control panel, control circuitry, control vault, regulator, primary cable, isolating transformer, secondary cable, fixture, lens, and lamp. Division of the model into components considered function, maintenance, physical proximity and connection, and failure mode. Some of the components include several elements (e.g., the control vault includes power transformers, relays, switches, etc.) while others are composed of a single element (e.g., the lamp). A lighting system may include a variable number of any of the component types.

By defining component operating and failure rate characteristics and the system configuration and failure criteria, any specific airfield lighting system can be analyzed using this general model.

Airfield Lighting System Operation

An airfield lighting system is designed to operate over a design life of some period, typically 15 to 20 years. Some of the components, however, are designed for lives considerably shorter than the system design life. Thus, maintenance is critical to the operation of airfield lighting systems. In fact, a recent study of airfield lighting found that without maintenance, total deterioration can result in 3 to 4 years.[1]

Maintenance performed on the systems is either corrective or preventive. Corrective maintenance entails repairing or replacing items of equipment which have failed. Preventive maintenance includes all activities performed prior to failure which ensure reliable operation of the system. The level of preventive maintenance and the speed of corrective maintenance directly influence the system's capacity to serve its design function.

Since airfield lighting systems undergo constant maintenance, their behavior becomes independent of the starting state after a period of

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[1] *Analysis of General Aviation Airports--Summary Report Task III* (Burns and McDonnell Engineering Company, August 1974).

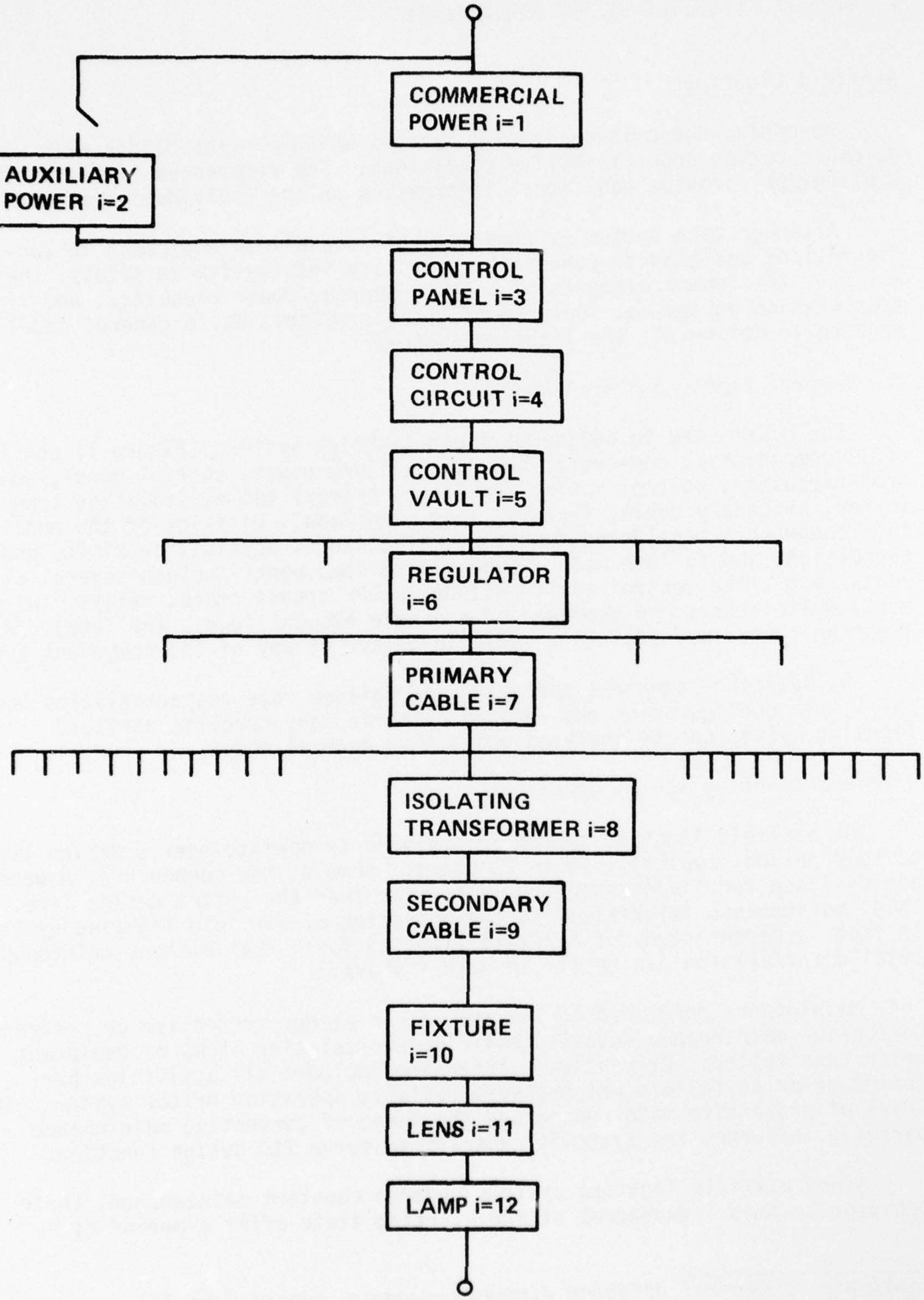


Figure 1. General lighting system model.

operation. In this condition, a system is composed of equipment of various ages, with each equipment item having an equal probability of being at any point in its design life at a given time. This condition is known as the steady state.

By assuming that a lighting system is operating in a steady state, the problem of analyzing its reliability becomes manageable. Typical component characteristics and failure rates can be estimated, and component reliability distributions can be determined using stochastic techniques. Proceeding in this manner, the reliability of a specific system can be evaluated for the conditions under which it operates.

Airfield Lighting System Failure

An airfield lighting system fails when it does not accurately transmit the information required by a pilot for safe operation of an aircraft. System failure can be due to components not functioning or to components operating at less than the designed condition and thereby transmitting false information to the pilot. Since pilot perception is involved, system failure is subjective, except in cases where the majority of lights are inoperable.

To provide objectivity to the failure criteria, the FAA has established minimum operating standards for individual lighting systems. Table 1 shows a sample of these standards.

Analysis of Reliability

System reliability is defined as the probability that a system will perform its intended function in a specified environment for a specified period of time. The steady-state reliability for airfield lighting systems can be interpreted as the probability of the system working when the switch is turned on. As such, reliability cannot be directly measured but must be estimated. Doing so requires knowledge of the following:

a. The equipment failure process

b. The equipment characteristics (including operation, geometry, and maintenance)

c. The state in which the system is defined as failed.

System reliability is thus a combination of the probabilities of success for each of the component items of equipment. In a series system such as the general lighting model, the system reliability is the product of the component reliabilities. Since the component reliabilities are generally less than 1.0, the system reliability decreases as the system becomes more complex (i.e., as more components are added). Defining each component's operation as accurately as possible is therefore imperative.

The reliability of each component type in the general lighting system model can be approximated by an exponential distribution over the component's

Table 1

Typical System Failure Criteria

System	Criteria
ALSF II	
Centerline bars	Two lamps out in five-lamp bar constitutes a bar failure.
	Two consecutive light bars failed or 20 percent random outages constitutes system failure.
Siderow bars	One lamp out in three-lamp bar constitutes a bar failure.
	Two consecutive light bars failed or 20 percent random outages constitutes system failure.
Threshold bar	Three adjacent lights or 20 percent random failures constitutes system failure.
500-foot (150-meter) bar	Same as threshold.
1,000-foot (300-meter) bar	Same as threshold.
Category II	
Centerline lights	Four consecutive outages or 10 percent random failures constitutes system failure.
Touchdown zone	Two consecutive bar failures or 10 percent random failures on either side of the centerline constitutes system failure.

design life (Figure 2). Since component reliability is a function of the component's failure rate, and since measurement of the failure rate is more practical than direct measurement of reliability, the reliability distribution in Figure 2 is normally determined as a function of failure rate, as shown in Eq 1.

$$R(t) = e^{-\lambda t} \qquad \text{[Eq 1]}$$

where $R(t)$ = the component reliability at time t

λ = the component failure rate

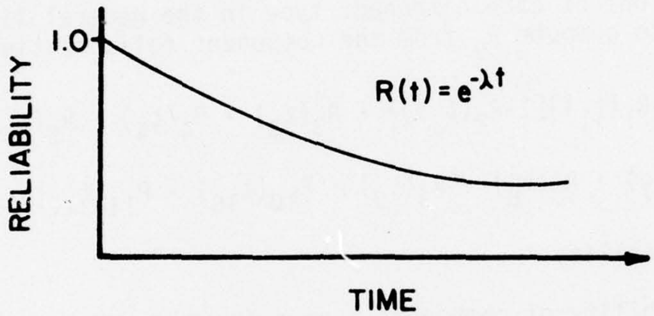


Figure 2. Reliability distribution.

Determination of the failure rate (λ) for each component in the system is quite complex when maintenance and operation practices are considered. Full-scale testing of lighting systems to determine failure rates would be expensive and time consuming, while accelerated testing of systems or individual components introduces inaccuracies. Thus, field data on system performance are the best source of information for determining a component's reliability function.

Considering the field data anticipated to be available, the reliability function for each component in the lighting system can be expressed by

$$R(t) = e^{\frac{-(t-t_s)C_m}{C_f}} \qquad \text{[Eq 2]}$$

where C_f = the coefficient of failure

C_m = the coefficient of maintenance

t_s = the safety time (i.e., the period of time when the component is known to have no chance of failure).

This expression empirically accounts for preventive maintenance, corrective maintenance, and failure rate. Preventive maintenance (PM) considers the component's design life, replacement time (i.e., that period preceding the design life when group replacement is undertaken), and, indirectly, the level of PM activities (i.e., the more PM performed, the lower the failure rate). Corrective maintenance includes the time to detect a failure and the time required to perform repairs. The failure rate is the annual number of failures to that component type in a system due to all failure modes (e.g., wear-out, human error, etc.). Appendix B describes the determination of component reliability and definition of the variables involved.

Once the individual component reliabilities have been determined, they can be combined to determine the average unit reliability. The unit reliability (R_u) is defined as the probability that a randomly chosen single unit in the system will be operational when called upon to perform. The unit is composed of one of each component type in the general lighting model. Equation 3 is used to compute R_u from the component reliabilities.

$$R_u = \left\{1 - [1-R_1(t_1)][1-R_2(t_2)]\right\} \cdot R_3(t_3) \cdot R_4(t_4) \cdot R_5(t_5) \cdot R_6(t_6) \cdot R_7(t_7) \cdot R_8(t_8) \cdot R_9(t_9) \cdot R_{10}(t_{10}) \cdot R_{11}(t_{11}) \cdot R_{12}(t_{12}) \qquad \text{[Eq 3]}$$

where R_u = unit reliability

$R_i(t_i)$ = the reliability of component i as a function of its time in service (t) where i indicates components 1 *through* 12 *in the* general model.

In evaluating the average unit reliability, it must be considered that the component's reliability is actually a function of time and that in the steady-state, the component's reliability can be at any point of time on the function. The system geometry or the number of each component type in the system must also be considered. A Monte Carlo simulation routine was developed to stochastically account for these factors. Appendix B includes this routine along with further information on unit reliability.

From the average unit reliability and the system failure criteria, the reliability of the lighting system can be determined from the following equation:

$$R_s = \sum_{i=0}^{n} W_i R_u^{n-i} (1-R_u)^i \qquad \text{[Eq 4]}$$

where R_s = the system reliability

R_u = the unit reliability

n = the total number of lights in the system

i = the number of light failures in the system

W_i = the number of ways i failures can occur in a system of n total lights without the system reaching failure by either the random or the consecutive failure criteria.

Appendix B includes a comprehensive description of the analytical procedure used to determine R_s.

Computerized Procedure

The reliability methodology summarized in the previous section was incorporated in an automated program capable of estimating the functional reliability of any lighting system used in the visual guidance of aircraft. This program, called RAALS (Reliability Analysis of Airfield Lighting Systems), can be efficiently used by airport managers, governing agencies, or maintenance personnel interested in determining airfield lighting system reliability. The analytical techniques developed can also be modified to evaluate the reliability of any complex system for which failure criteria stipulate consecutive failures as well as random failures.

3 FINDINGS

RAALS Program

The automated procedure for analyzing airfield lighting system reliability developed in this study is an implementable tool which can be used to:

a. Compare the reliability of similar systems at various airports

b. Determine where a system should be improved to increase its reliability

c. Form a basis for decisions on implementing changes to failure criteria, equipment, or maintenance policies

d. Monitor the reliability of a system as it becomes older or as modifications are installed.

Presently, the RAALS program is operating on the CDC 6600 series computer, but the user can modify it to operate on other hardware.

RAALS Input

The input data necessary to evaluate a system's reliability with the RAALS program include:

a. The number of each type of component in the system (i.e., the system geometry)

b. The number of failures per year for each type of component

c. The design life for each type of component

d. The safety time for each component (i.e., the period following installation when the reliability is 1.0)

e. The replacement time for each component (i.e., the period of time the component is expected to be operational)

f. The operation criteria in hours per day and days per year

g. The system failure criteria.

RAALS Logic

The RAALS program logic is based on traditional reliability theory. However, due to the number and complexity of lighting systems and the necessity to consider consecutiveness in the failure criteria, original analytical techniques were developed and interfaced with traditional theory. These techniques included:

a. Formulation of a general lighting system model capable of considering all of the diverse equipment and geometry encountered in airfield lighting

b. Adaptation of a Monte Carlo simulation routine to the analysis to account for the stochastic nature of the component reliabilities

c. Derivation of the consecutive coefficient to consider consecutiveness in the system failure criteria (see Appendix C)

d. Development of an analytical procedure to determine system reliability which accounts for the operation, maintenance, and failure variables of each component

e. Automation of the combined procedures into a concise, efficient computer program.

Appendix D provides the program documentation and an example problem.

Field Investigation

Making reliability evaluations for any system requires knowledge of the failure rate of the component equipment in the system. This knowledge requires constant orderly feedback of information from the field. A limited field investigation was conducted to determine what types of information are presently being collected. It was anticipated that present maintenance records could be analyzed with the RAALS program to predict the reliability of existing lighting systems.

The FAA maintains the Visual Approach Slope Indicator (VASI) and the lighting systems in front of the runway thresholds while individual airport agencies maintain all other systems. Both the FAA and airport maintenance staffs keep maintenance logs on performance checks, corrective repairs, and preventive maintenance. However, the data examined during the field investigation were sparse. The logs being kept did not provide all the input data needed for the reliability analysis. Based on discussions with field personnel, however, the missing data were estimated subjectively. These data were used as the basis for the example problem in Appendix D and the sensitivity analysis in Appendix E. Since historical records of component failures were limited, further analysis of field data was not undertaken.

The following observations can be made based on the field investigation:

a. FAA records are standardized, while each airport maintenance staff develops its own format for record-keeping. Thus, for a reliability analysis procedure to be universally implementable, standardized maintenance record-keeping should be initiated. Otherwise, the data on each individual system must be manipulated to fit the reliability analysis procedure's format. This will entail subjective judgments which will introduce ambiguities in the comparison of lighting systems at different sites.

b. Recording of maintenance data is hampered by several factors. Maintenance personnel often feel they barely have time to keep up with current corrective repair activities and therefore have little time for extensive record-keeping. Since some failures are recorded prior to determination of the cause, the records may show a light out when the failure was actually in the isolating transformer or some other component. In addition, when some failures are corrected, the maintenance personnel make no record of the occurrence because it was not considered critical or because they feel a record of numerous failures would adversely affect the staff performance rating.

c. Both FAA and airport maintenance staffs generally believe that their lighting systems are reliable. Because of this belief, field personnel feel that recording supportive data is an unnecessary burden.

Sensitivity Analysis

A sensitivity analysis of the variables affecting the reliability of lighting systems was performed using the RAALS program. The results presented in this section are aimed at answering typical management questions regarding system reliability. Appendix E contains a detailed discussion of the sensitivity analysis.

Failure Criteria

A lighting system's reliability is based on the failure criteria used. The failure criteria are stipulated as a percentage of random failures and a number of consecutive failures. Relaxing either criterion increases system reliability.

Since the relationship between the failure criteria and system reliability is not linear, only trends can be used to illustrate the sensitivity. Figure 3 shows the effect of relaxing the percentage of random failures while Figure 4 shows the effect of relaxing the number of consecutive failures. In general, the random failure criterion governs when the consecutive failures allowed are greater than 5 and random failures are less than 25 percent. Conversely, when the consecutive criterion is less than 3, it generally governs.

This discussion is of course not an argument to relax the failure criteria in order to improve reliability. Minimum information conveyance standards must be established for each system based on pilot perception. However, these trends do illustrate the effect on system reliability should changes in the failure criteria be justified.

Unit Reliability

Figure 5 shows the relationship between unit reliability and system reliability for a standard set of operating characteristics and failure criteria. As the figure shows, when system reliability is low (R_S less than .96), a small increase in unit reliability results in a large improvement

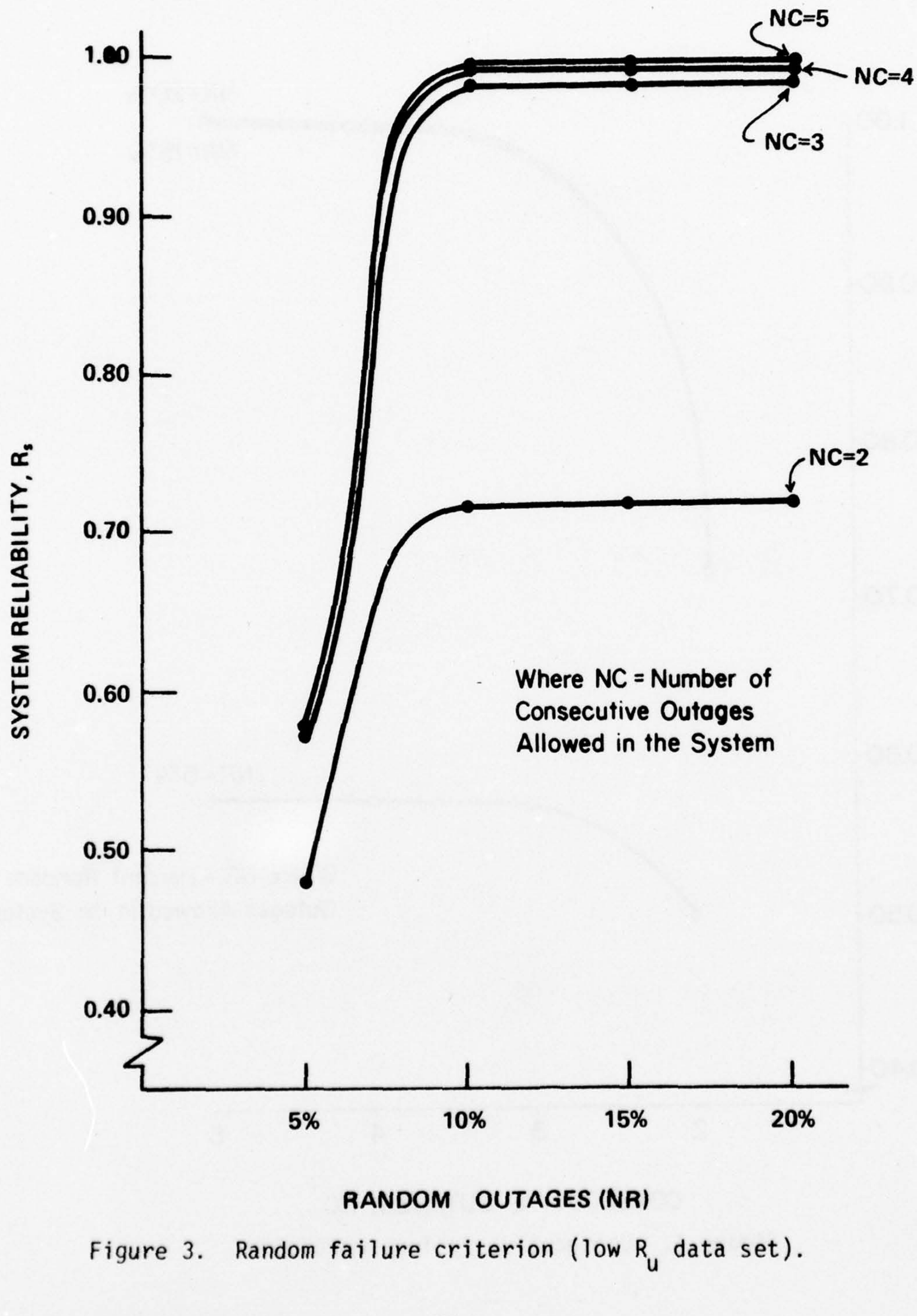


Figure 3. Random failure criterion (low R_u data set).

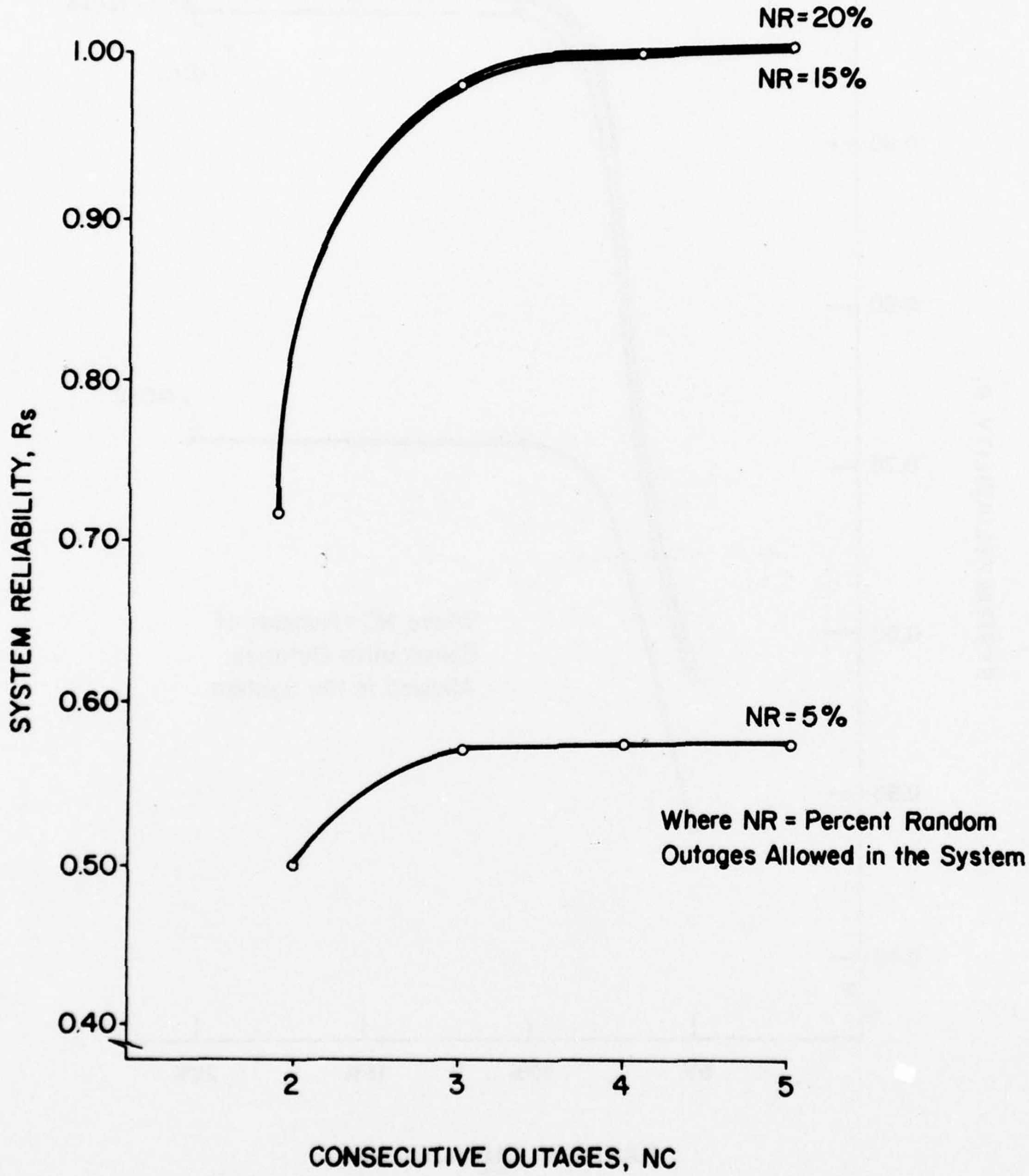


Figure 4. Consecutive failure criterion.

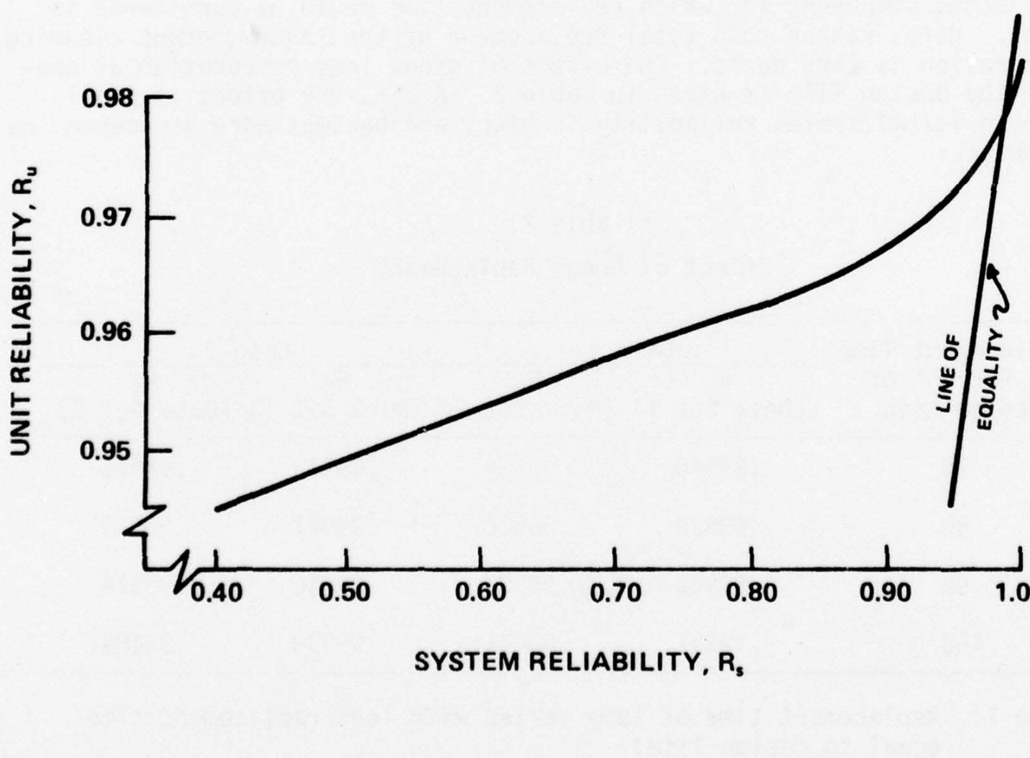


Figure 5. R_u vs. R_s.

in system reliability. For example, improving unit reliability by .01 (from .95 to .96) results in a system reliability increase of .22 (from .54 to .76). However, when system reliability is high, increases in unit reliability are much less significant.

Although unit reliability can be used to illustrate the sensitivity of system reliability from an analytical standpoint, it cannot be used as a sole measure of merit for improvements to the system because numerous variables influence R_u. Some of these variables can be controlled while others cannot; the following sections discuss the sensitivity of R_s to some of the controllable variables.

Group Replacement

Group replacement is a preventive maintenance practice involving replacement of all components of a particular type at a specified time prior to the component's design life. Group replacement of a component will improve the reliability of that component, thereby increasing unit and system reliability. Typically, the lamp component is considered for group replacement. Table 2 shows the effect of group relampment at 70, 80, 90, and 100 percent of the lamp's design life for two systems. For a standard centerline runway system (data set 1), group relampment provides only a small improvement. For a second system with lower reliability (data set 2), the effect is more pronounced.

A second component for which replacement time could be considered is the lens. Here, rather than total replacement of the lenses, group cleaning or restoration is considered. The effect of group lens restoration at one-half of the design life is given in Table 2. Again, the effect is small when the original system reliability is high, and becomes more pronounced as R_s decreases.

Table 2

Effect of Group Replacement

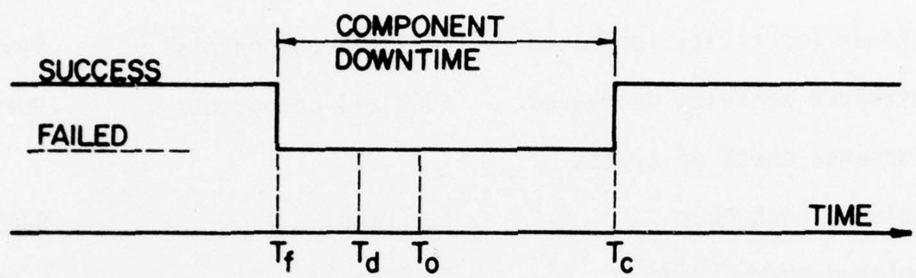
Replacement Time as Percent of Design Life	Case 1		Case 2	
	R_s (Data Set 1)	R_s (Data Set 2)	R_s (Data Set 1)	R_s (Data Set 2)
70	.99940	.98534	.99942	.98576
80	.99939	.98520	.99941	.98559
90	.99938	.98501	.99940	.98524
100	.99937	.98471	.99939	.98488

Case 1: Replacement time of lamp varied with lens replacement time equal to design life.

Case 2: Replacement time of lamp varied with lens replacement time equal to one-half design life.

Downtime

Corrective maintenance activities are considered in the analysis using the downtime variable. Downtime is defined as the average length of time a component is inoperable following failure. Four points in time are included in the downtime: time of failure, time of detection, time of removal of the system from operation, and time of repair or replacement. These points are illustrated in Figure 6. If the component failure does not constitute system failure, the time of removal of the system from operation does not occur ($T_o = T_c$).



where T_f = time of failure

T_d = time of detection

T_o = time system removed from service

T_c = time failure is corrected

Figure 6. Periods within component downtime.

Table 3 presents system reliability data resulting from changes in the downtime for the stated reasons.

Full monitoring of a lighting system would result in T_d equal to T_f, which would decrease the downtime for all components. Assuming a decrease in the downtimes of 20 percent for all components would result in an increase of .000282 in the system reliability for this data set.

If maintenance activities were either increased or decreased, the system reliability would be affected as shown in Table 3. Note that decreasing the downtime for all components by 50 percent results in an increase in R_s of .000585, while an increase of 50 percent results in a decrease in R_s of .008238.

Changing the frequency of checking light operation and replacement of failures from daily (every 12 hours) to every hour during the operating period would improve system reliability by .000108, while changing to every other day (every 24 hours) would decrease it by .00140.

Table 3

Downtime vs. System Reliability

Reason	Change in Downtime	R_s
Standard data set	--------	.999395
System monitored	-20% all components	.999677
Maintenance activity increased	-50% all components	.999980
Maintenance activity decreased	+50% all components	.991157
Performance check of lights		
--replaced each hour	T_D (Lamp) = 1	.999503
--replaced every 12 hours	T_D (Lamp) = 12	.999395
--replaced every 24 hours	T_D (Lamp) = 24	.999255

Failure Rate

Table 4 indicates the sensitivity of system reliability to changes in the failure rate of the lamp, isolating transformer, and regulator components. These types of changes could result from an inferior shipment of equipment or from exposure to atypical weather conditions (e.g., electrical storms) which create an increased number of failures.

Table 4

Failure Rate vs. System Reliability

Component	Number of Failures per Year	R_s
Lamp	75	.999455
Lamp	150	.999395
Lamp	250	.999306
Isolating transformer	0	.999419
Isolating transformer	15	.999395
Isolating transformer	30	.999367
Regulator	0	.999507
Regulator	3	.999395
Regulator	9	.999103

4 CONCLUSION

The automated tool produced in this research can be used to evaluate the functional reliability of any airfield lighting system. This computer program, RAALS, includes the necessary analytical procedures for determining reliability in an efficient, economical manner. The program output can be used directly by the FAA or any airport agency to measure the merit of individual systems and the effectiveness of maintenance activities.

Testing of the RAALS program did not indicate a need for modification in equipment or operation to any of the lighting systems examined. However, improved and standardized maintenance recordkeeping procedures for all lighting systems are needed. Efficient collection, analysis, and reporting of performance data will aid in improving lighting system reliability by indicating where problems exist and where maintenance activities, both corrective and preventive, should be increased to optimize the cost-benefit ratio.

APPENDIX A:

VISUAL GUIDANCE LIGHTING SYSTEMS

System Characteristics

Aircraft movements are guided by numerous lighting systems, each of which is designed for a specific purpose; that is, each conveys certain required information to the pilot. Thus, the geometry, number of lights, and individual equipment items vary depending on the information to be conveyed by the system. In addition to these physical differences, each lighting system also has unique failure criteria. These criteria subjectively establish minimum operating standards for each system to achieve its designed purpose.

The principal lighting systems governing aircraft movements are:

a. Approach lights
b. Vertical Approach Slope Indicators (VASI)
c. Threshold lights
d. Touchdown lights
e. Runway edge lights
f. Runway centerline lights
g. Taxiway edge lights
h. Taxiway centerline lights.

In addition, rotating beacons, runway identification lights, obstruction lights, apron lighting, and special site-specific lighting (e.g., displaced threshold) also aid in the safe, efficient movement of aircraft.

Figures A1 through A5 illustrate typical geometric configurations for the principal types of lighting systems. Although the number of lights varies widely, the configuration of each system's lights can be categorized as either linear or bar.

Linear systems contain a string of single lights. The threshold, centerline, edge, and approach sequenced flasher lighting systems fall into this category. Failure criteria for this category are typically stated as the percent of random outages causing system failure and the number of consecutive outages causing system failure.

Bar systems contain groups of lights arranged in light bars. The VASI and the wing, centerline, 500-ft (150-m), 1000-ft (300-m), and terminating bars of the approach and touchdown zone light systems are included in this category. The failure criteria for this category typically include the percent of random outages causing system failure, the number of consecutive bar failures causing system failure, and the number of outages in a bar causing bar failure.

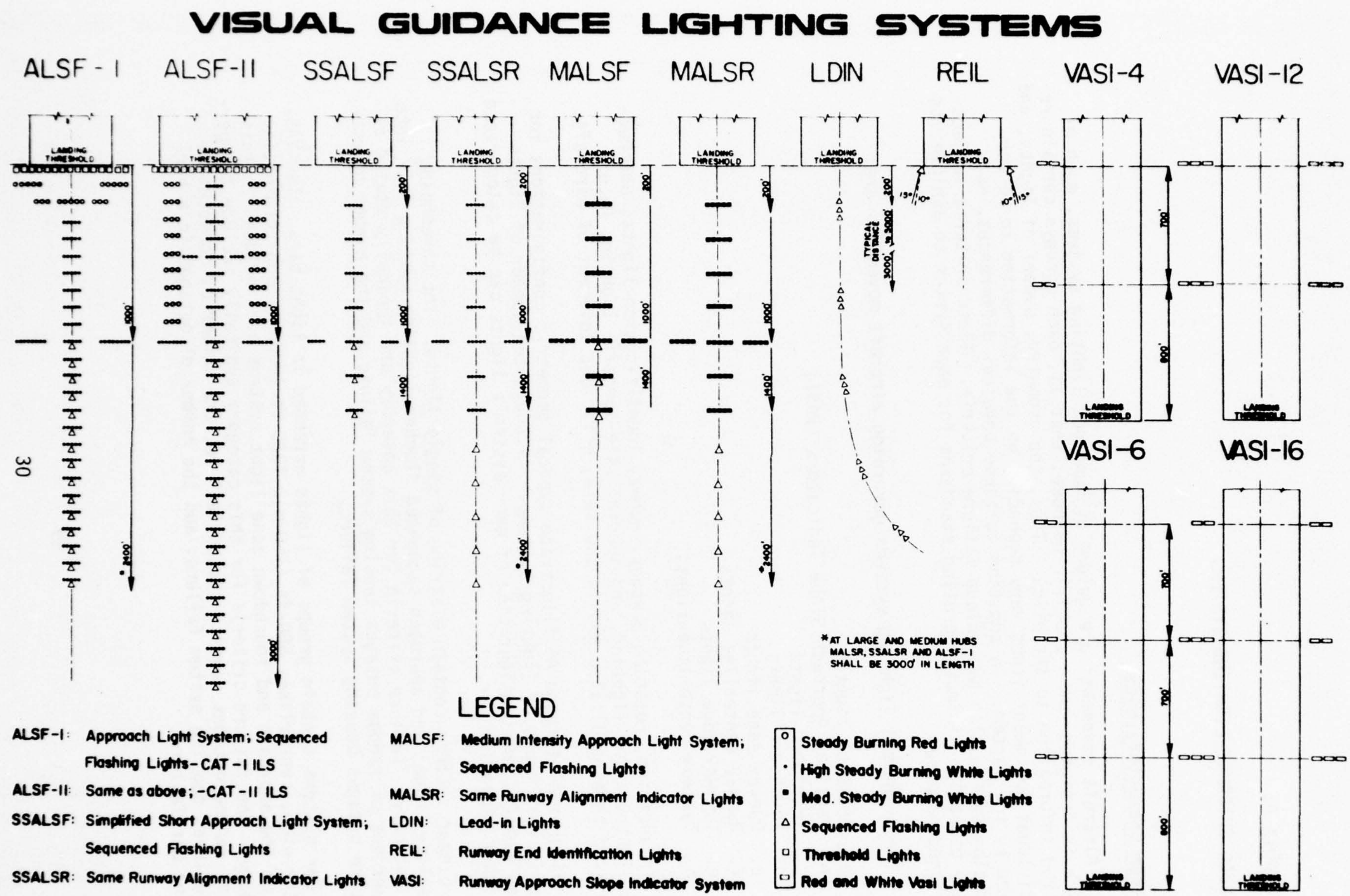
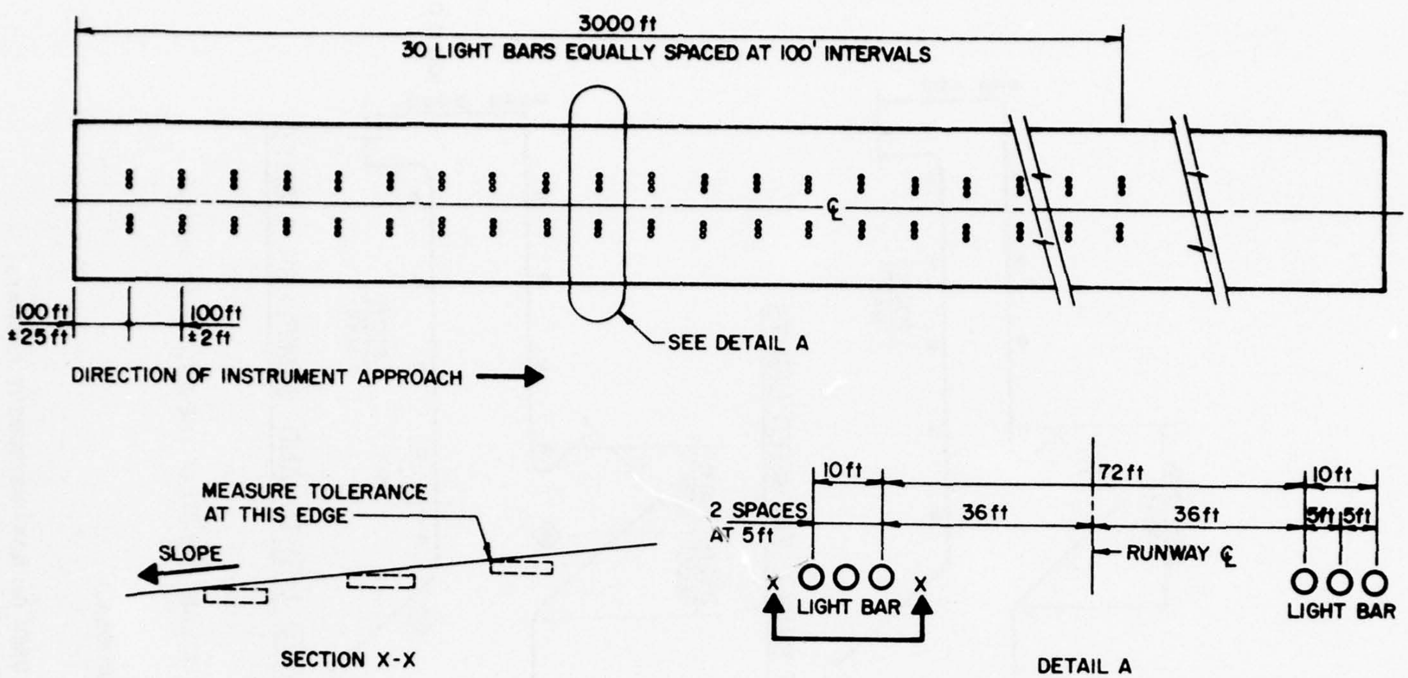


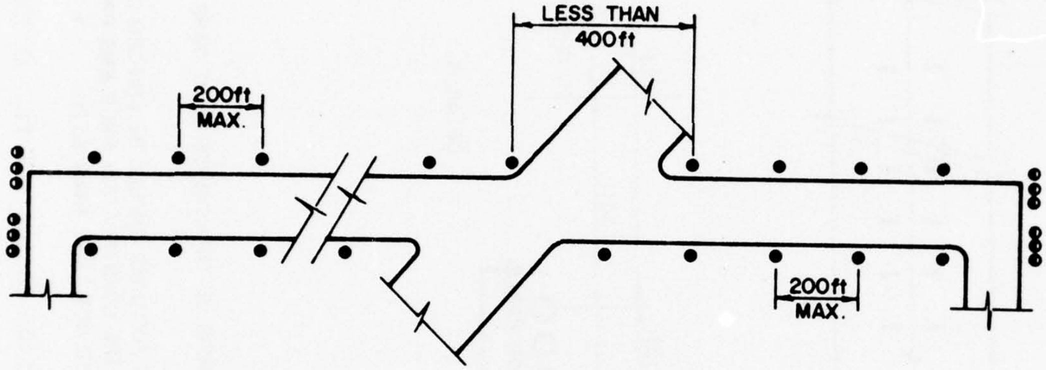
Figure A1. Approach light and VASI system. SI conversion factor: 1 ft = 0.3048 m.



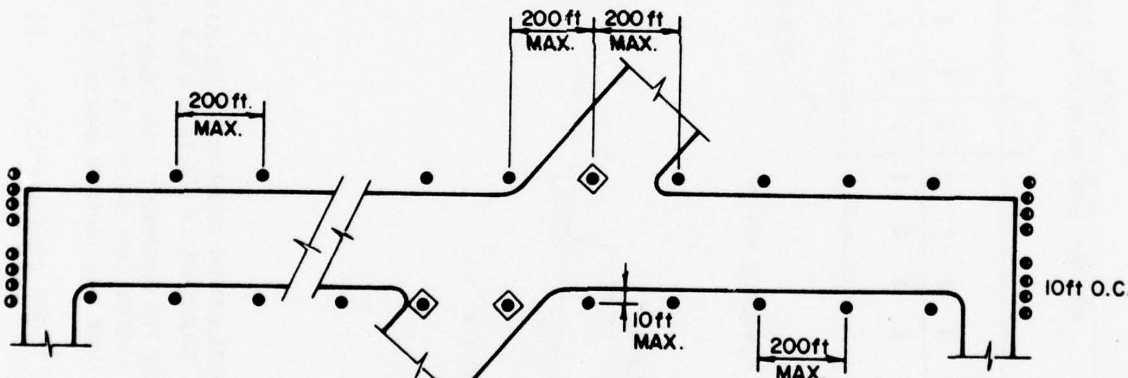
NOTES:

1. THE LONGITUDINAL INSTALLATION TOLERANCE IN LOCATING THE PAIRS OF TRANSVERSE LIGHT BARS SHOULD NOT EXCEED 2ft LATERAL TOLERANCE OF LIGHTS IN A BAR IS ± 1/4 in.
2. THE SPACING BETWEEN THE INNERMOST TOUCHDOWN ZONE LIGHT FIXTURES SHOULD BE UNIFORM THROUGHOUT THE LENGTH OF THE SYSTEM. THIS SPACING IS 72 ft EXCEPT WHERE CONSTRUCTION PROBLEMS PREVENT THIS SEPARATION IN THIS CASE. THE UNIFORM SPACING IS REDUCED TO NOT LESS THAN 65 ft.

Figure A2. Touchdown zone light configuration. SI conversion factor: 1 ft = 0.3048 m.



APPLICATION OF SINGLE ELEVATED LIGHTS



APPLICATION OF SINGLE ELEVATED LIGHTS AND SEMIFLUSH LIGHTS

LEGEND:

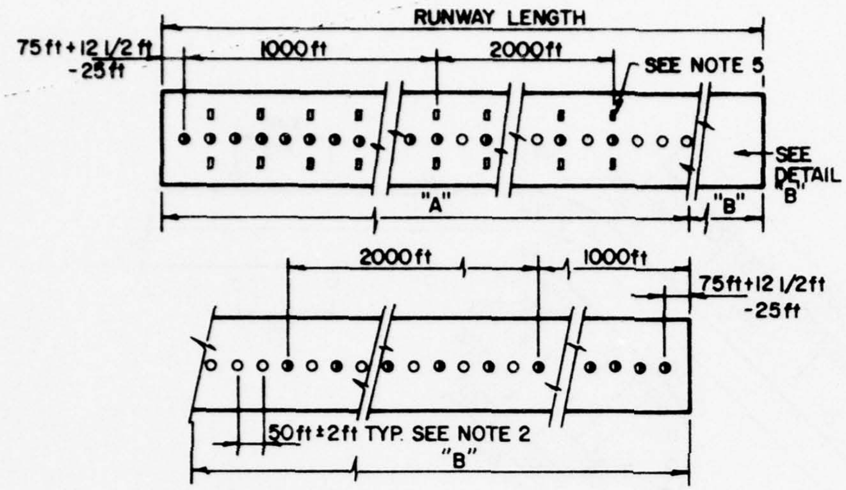
●---360° WHITE, EXCEPT FOR THE LAST 2,000ft OF THE INSTRUMENT RUNWAY

R◐G--RED 180° AND GREEN 180°

◆ -- SEMIFLUSH FIXTURE BIDIRECTIONAL

NOTE: SIX THRESHOLD LIGHTS USED ON NON-INSTRUMENT RUNWAYS
EIGHT THRESHOLD LIGHTS USED ON INSTRUMENT RUNWAYS

Figure A3. Typical high-intensity runway edge light (HIRL) configuration. SI conversion factor: 1 ft = 0.3048 m.



DETAIL "B"

SYMBOLS

- ▯ Unidirectional touchdown zone light bar, 3 lights per bar
- ○ Bidirectional runway centerline light white both directions
- r●w Centerline lights white (w) one direction and red (r) opposite direction

NOTES

1. Centerline lights may be offset 2ft to the right or left of the runway centerline to avoid the centerline paint markings.
2. The centerline lights may have a longitudinal tolerance of ± 2ft, a lateral tolerance of ± 1/4 inch.
3. The last 3000ft to 1000ft section of the runway centerline displays an alternate red and white light signal.
4. The last 1000ft section of the runway centerline displays an all red signal.
5. The touchdown zone light bars are not required to be located at the same stations as the centerline lights. See Figure A2 for configuration.

Figure A4. Runway centerline and touchdown zone light configuration. SI conversion factor: 1 ft = 0.3048 m.

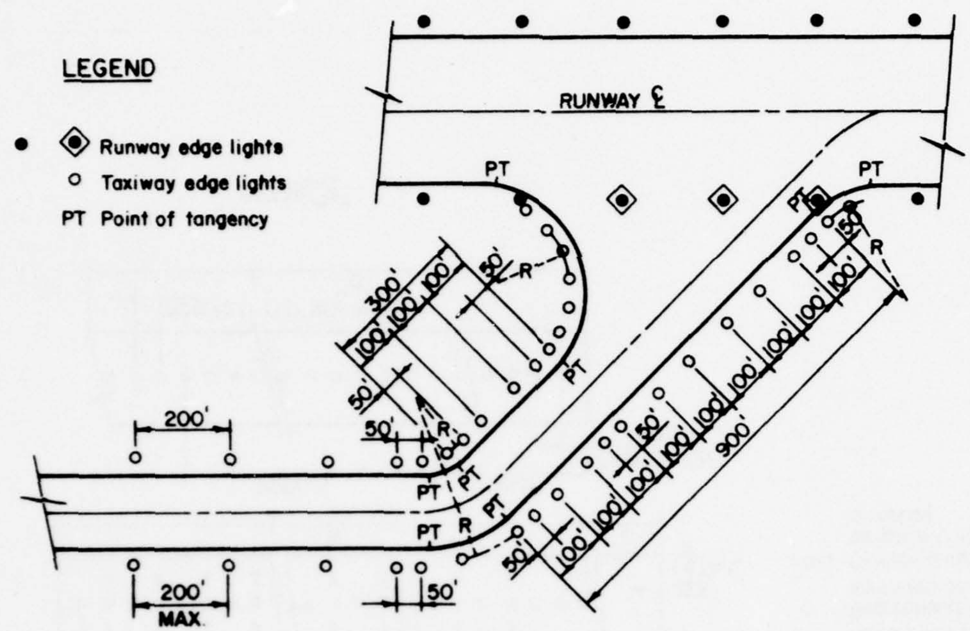


Figure A5. Typical taxiway edge lighting configuration. SI conversion factor: 1 ft = 0.3048 m.

General Lighting System Model

Although the systems discussed above have different configurations, number of lights, and failure criteria, all require a power source, electrical circuitry, and elements for light dispersion. Because of these similar requirements, a general lighting system model can be developed which is sufficiently flexible to account for the physical and failure criteria differences. Figure A6 shows the general model adopted for analyzing system reliability. This model, which has been divided into 12 components, can be used to describe all the linear and bar lighting systems. Figure A7 illustrates the model components as applied to the runway centerline system.

Division of the general lighting system into components considered function, maintenance records and practices, physical proximity and connection, and equipment failure modes. Some of the 12 components are composed of a single element (e.g., lamp), while others include several elements (e.g., the control vault includes transformers, relays, time switches, meters, etc.).

Using this model, the operation of any airfield lighting system can be defined by the characteristics of each of the 12 components, the system geometry, and the system failure criteria.

Component Characteristics

Typical failure modes and their significance to system operation are defined in Table A1 for each of the 12 components in the general lighting system model. A single failure in any of the equipment in the first seven components normally constitutes a system failure. However, multiple failures of the remaining components are required before the system is classified as failed. To characterize the components in a specific system, the total number of these failures and other operational data must be defined. Table A2 tabulates the data necessary to characterize each component.

Maintenance

The general model depicts an airfield lighting system as an arrangement of 12 types of components, with variable numbers of each component. The design lives of the component types are not identical, and are generally less than the system's design life. In addition, every component in the system does not operate over its entire design life, but fails with some frequency distribution over time. Figure A8 shows a typical failure distribution. This distribution provides the proportion of the total initial number of a component type which will be operating at any given time in the design life, or the probability of a component operating at a given time. Combining all the considerations discussed above results in a set of operation curves, as shown in Figure A9 for the general lighting system model.

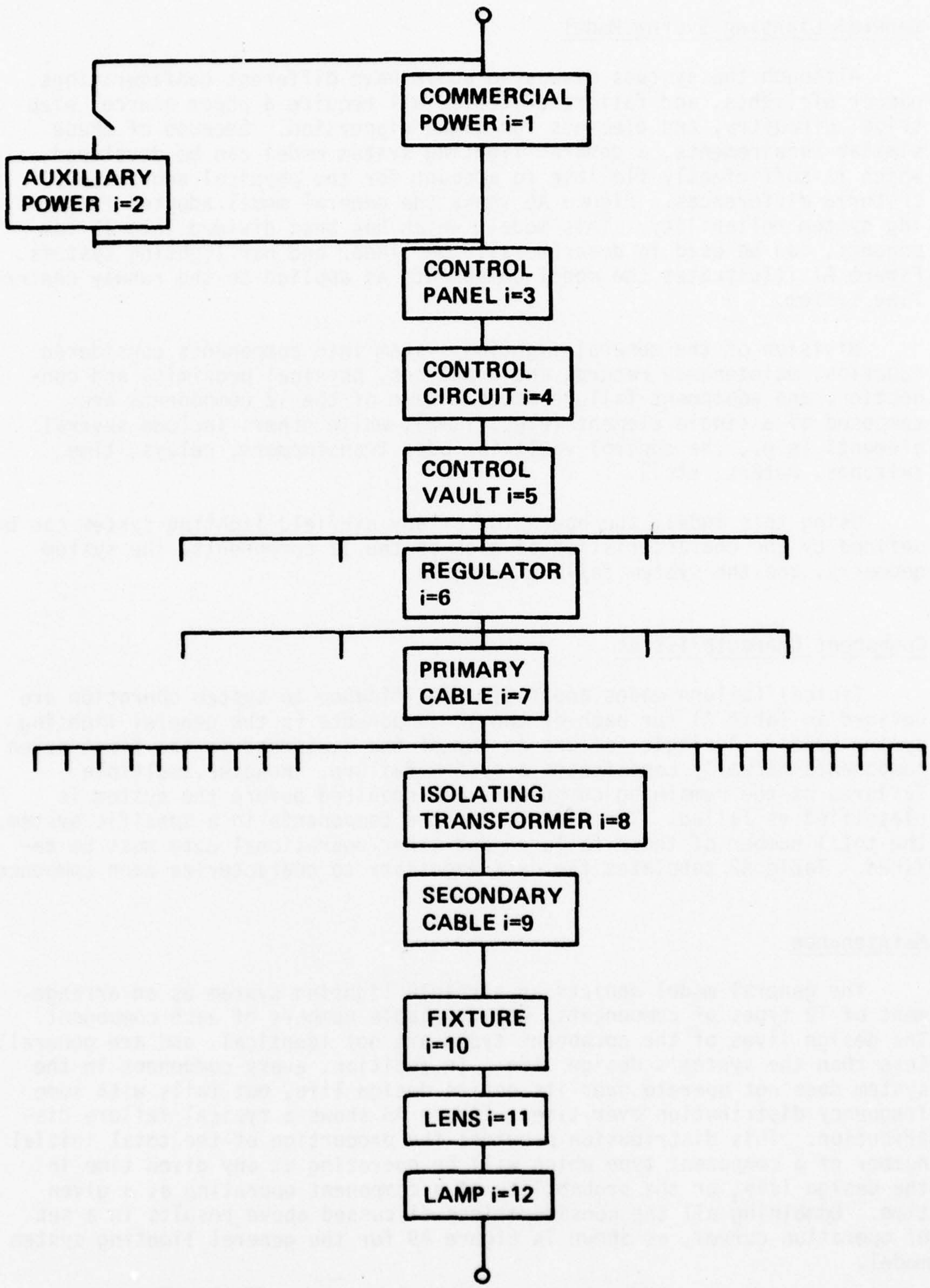


Figure A6. General lighting system model.

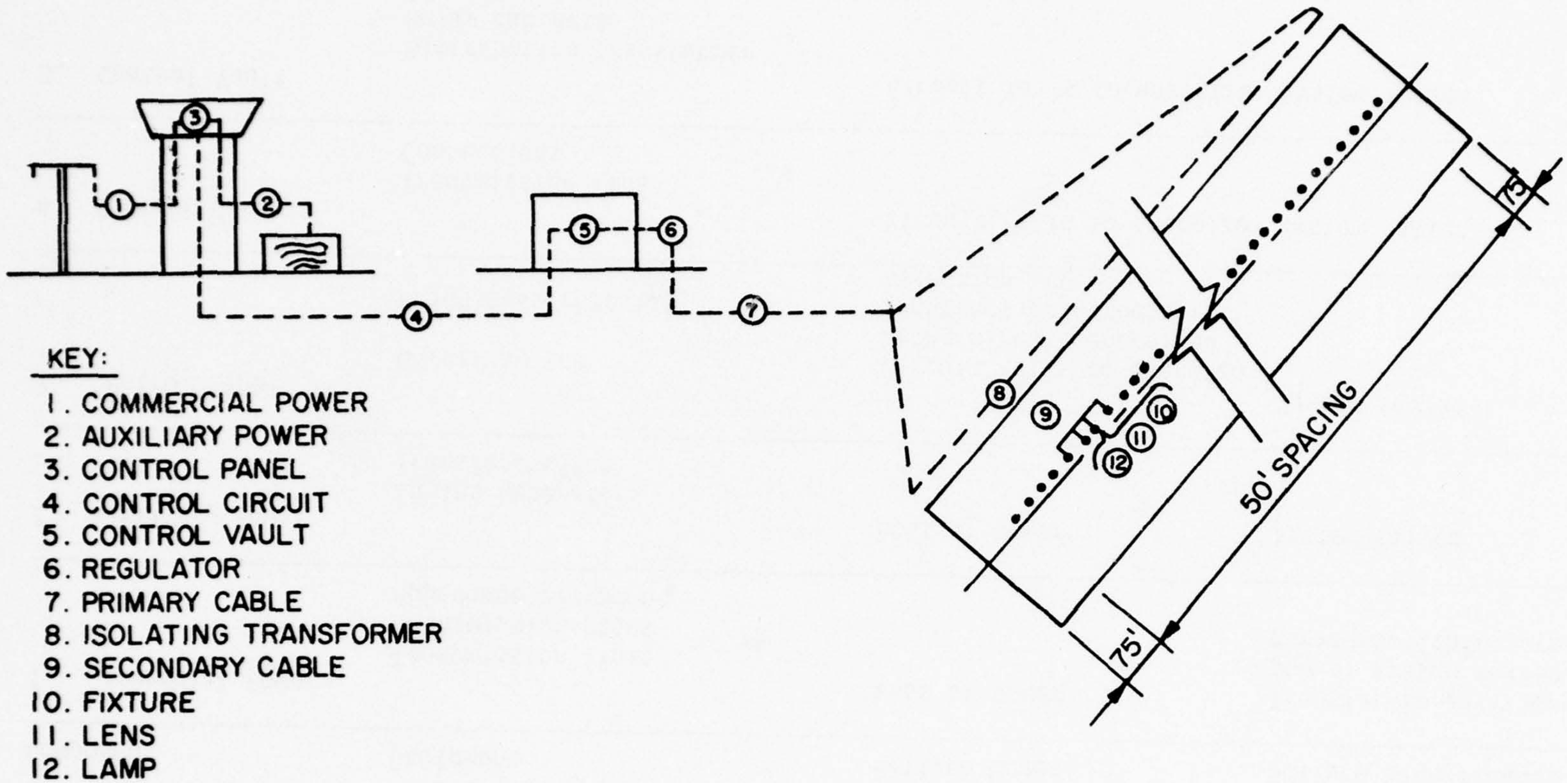


Figure A7. Runway centerline lighting system. SI conversion factor: 1 ft = 0.3048 m.

Table A1

Typical Component Failure Data

Component	Equipment	Failure Modes	Failure Significance
1. Commercial Power	Transmission lines Transmission poles Appendage equipment	Loss of power	Transfer to auxiliary power; system failed during switching process.
2. Auxiliary Power	Engine generator Transfer switch	Loss of power	System failed
3. Control Panel	On/off switch Brightness rheostat	Circuit fails to energize Wrong circuit energized Incorrect brightness selection	System failed
4. Control Circuit	Transmission lines Connections	Circuit fails to energize	System failed
5. Control Vault	Distribution transformer Relay cabinets Circuit selectors	Circuit fails to energize	System failed

Table A1 (cont'd)

Component	Equipment	Failure Modes	Failure Significance
6. Regulator	Regulator	Primary circuit fails to energize	System failed
7. Primary Cable	Cable -- conduit encased -- direct burial Connectors	Primary circuit deenergized because of frost heaving, severed by a contractor, solvent damaged insulation, rodent damage	System failed
8. Isolating Transformer	Isolating transformer	Failure on primary side -- open primary circuit Failure on secondary side -- open secondary circuit	System failed Light connected to secondary cable fails
9. Secondary Cable	Cable -- conduit encased -- direct or saw kerf Connectors	Same as primary cable	Light connected to secondary cable fails
10. Fixture	Base Gaskets, O ring, sealant Lamp housing and connections Cover or lens holder Standard	Snow plow damage Obscured by vegetation Vandalism Damaged during maintenance Salt corrosion	Single light fails

Tabe Al (cont'd)

Component	Equipment	Failure Modes	Failure Significance
		Misalignment Water ingress causing corrosion, shorting, or freezing	
11. Lens	Lens	Contamination from rubber, dirt, fuel, birddroppings Breakage from thermal shock, impact, hydrostatic pressures Weathering Scratching from sand blasting, sweeping equipment, and flying debris Vandalism	Single light fails
12. Lamp	Lamp	Lamp burn-out Lamp blackening Lamp breakage Vandalism Loss of intensity	Single light fails

Table A2

Component Characteristics

System: ____________________ Failure Criteria: ____________________

Location: ____________________ ____________________

Operation: ______ hours per day

Component	Number	Design Life (yrs)	Avg. Time to Replacement (hrs)	Safety Time (hrs)	Number Failures per Year	Avg. Downtime per Failure (hrs)
1. Commercial Power						
2. Auxiliary Power						
3. Control Panel						
4. Control Circuit						
5. Control Vault						
6. Regulator						
7. Primary Cable						
8. Transformer						
9. Secondary Cable						
10. Fixture						
11. Lens						
12. Lamp						

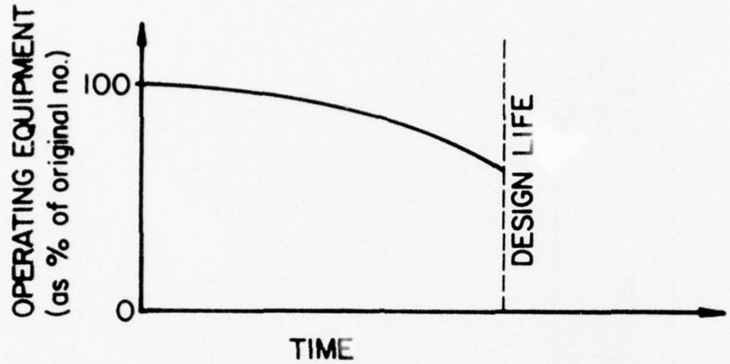


Figure A8. Typical failure distribution for a single component type.

As Figure A9 shows, for a lighting system to function over its intended design life, periodic repair and replacement of components is necessary. Thus, after a period of operation, the lighting system is comprised of equipment items of varied ages, and its behavior becomes independent of its starting state. This condition is known as the steady state in which at any given time, a component may be considered at any stage in its design life with equal probability.

The steady state which a lighting system reaches depends on the maintenance performed on the system. This maintenance takes two forms: preventive and corrective. Preventive maintenance includes those activities performed while the component equipment is in service to prevent deterioration and ensure reliable operation. The level of preventive maintenance performed is reflected in the equipment's failure distribution. Corrective maintenance encompasses the repair or replacement of defective components.

Because the airfield lighting systems are maintained systems, analysis of their reliability is complicated by interactions among the diverse system and component characteristics. Appendix B presents the methodology used to account for these interactions in evaluating the system reliability.

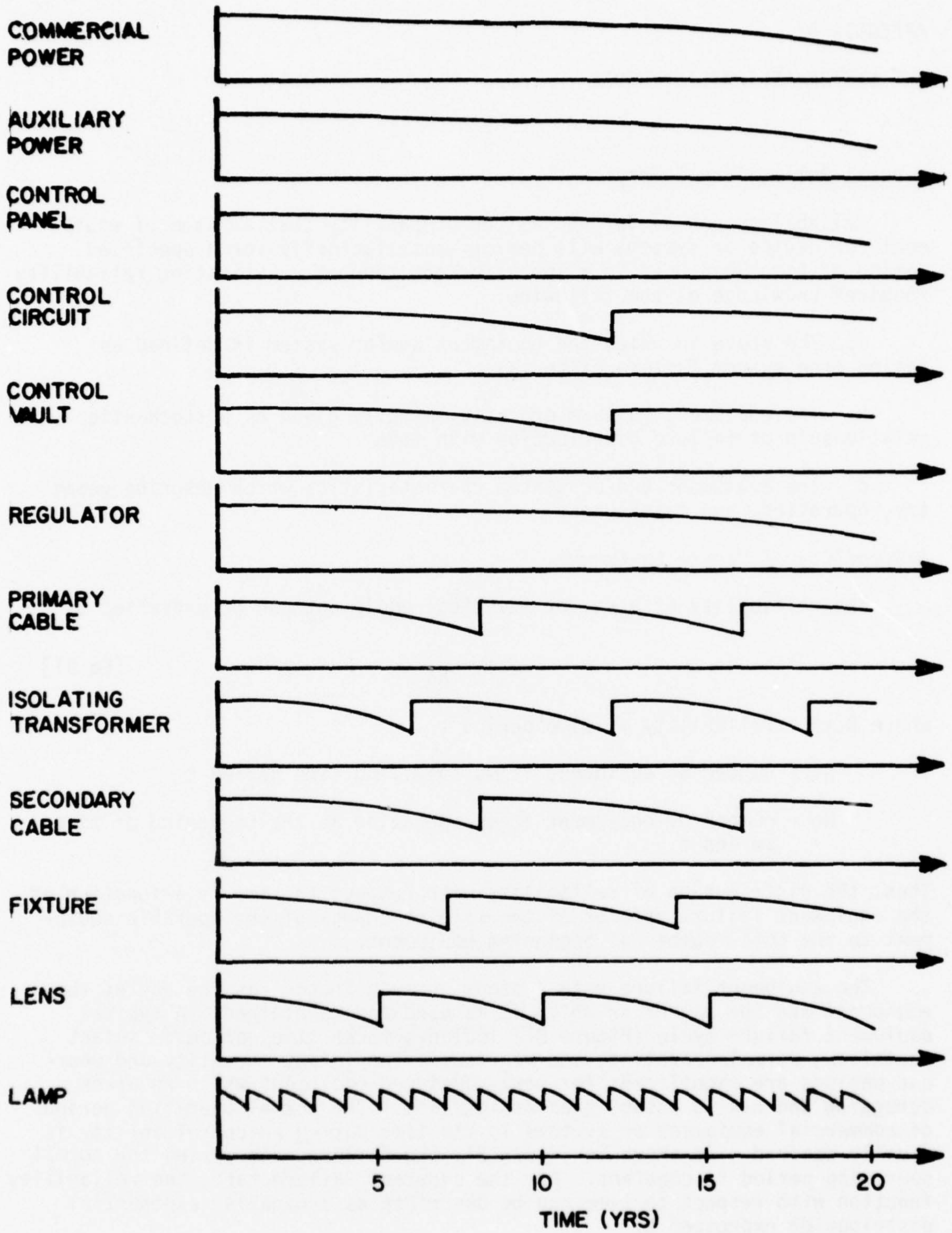


Figure A9. Component operation curves.

APPENDIX B:

THE SYSTEM RELIABILITY MODEL

General Reliability Theory

Reliability can be defined as the probability that an item of equipment (or device or system) will perform satisfactorily for a specified period of time when used in a specified environment. Estimating reliability requires knowledge of the following:

a. The state in which the equipment and/or system is defined as failed (the system failure criteria)

b. The equipment failure process, normally given as a stochastic relationship of failure distribution with time

c. The equipment and/or system characteristics which describe geometry, operation, and maintenance.

Reliability of Single Equipment

The reliability of a set of identical equipment can be expressed as

$$R(t) = \frac{Ns}{No} \qquad \text{[Eq B1]}$$

where R(t) = reliability at time period t

Ns = number of equipment items surviving time period t

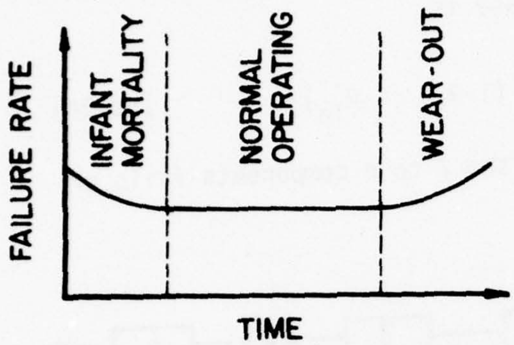
No = number of equipment items operating at the beginning of time period t.

Thus, the distribution of reliability with respect to time is a function of the equipment failure rate or of the rate of change of the operable equipment to the total number of beginning equipment.

The equipment failure rate depends on such factors as the age of the equipment and the manner in which it is used and maintained. A typical equipment failure cycle (Figure B1) includes three time periods: infant mortality, normal operating, and wear-out. The infant mortality and wear-out periods are significant for newly designed equipment which requires debugging and has no established design life. The normal operating period of commercial equipment or systems is the time during which reliability is usually desired. As shown in Figure B1, the failure rate during the normal operating period is constant. For the constant failure rate, the reliability function with respect to time can be described as a negative exponential distribution expressed by

$$R(t) = e^{-\lambda t} \qquad \text{[Eq B2]}$$

Figure B2 illustrates this distribution.



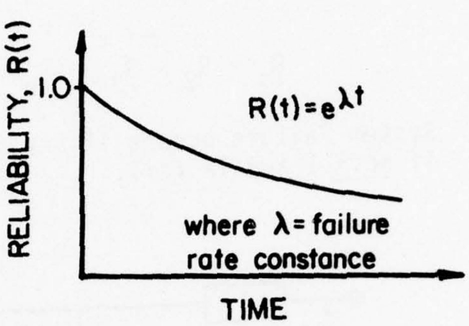


Figure B1. Typical equipment failure cycle.

Figure B2. Typical reliability function.

For a given item of equipment, determination of the failure rate (λ) can be complex. When the equipment also undergoes maintenance and replacement during an operating period, that determination becomes even more complex.

Reliability of Connected Equipment

Since the reliability of a system of interconnected equipment items is usually more significant to the user than the individual reliabilities, techniques for combining the individual component reliabilities are necessary. In general, a system is composed of equipment linked in series, parallel, or a combination of the two.

Figure B3 illustrates a series system. The system reliability of this arrangement is given by the product of the individual reliabilities or

$$R_s = R_1 \cdot R_2 \cdots R_n \qquad \text{[Eq B3]}$$

Note: System failure occurs if any one of the n items of equipment fail.

Figure B3. Series system.

Figure B4 presents a special case of a series system which includes a standby redundant component. That is, when component 1 fails, a switch, which is assumed to never fail, is closed and component 1a completes the series. The system reliability for this case is

$$R_s = R_2 \cdot R_3 \cdot\cdot R_n \cdot \left\{1 - (1-R_1)\,(1-R_{1a})\right\} \qquad \text{[Eq B4]}$$

Note: System failure occurs if any one of the 2 to n components fails or if <u>both</u> 1 and 1a fail.

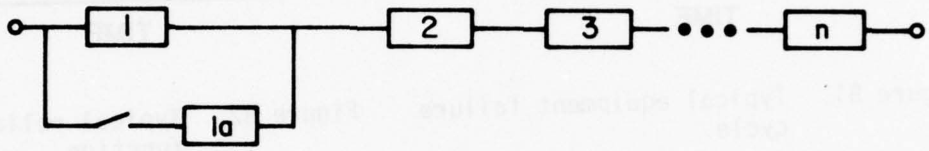


Figure B4. Series system with standby redundant component.

Figure B5 illustrates a parallel system whose reliability is expressed by

$$R_s = 1 - \prod_{i=1}^{n} (1-R_i) \qquad \text{[Eq B5]}$$

where Π denotes the product of the $(1-R_i)$ terms.

Note: System failure occurs only when all of the n items of equipment fail.

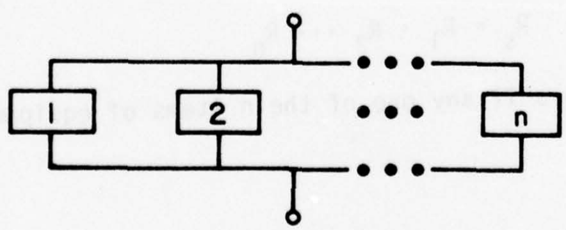


Figure B5. Parallel system.

As Eqs B3, B4, and B5 indicate, the probability of successful operation of the system depends on the probability that all component equipment in the system operates successfully. This implies that the greater the complexity of the system, the lower the system reliability.

It should also be noted that the component reliability terms in these equations actually represent points on the equipment's reliability function (Eq B2). Thus, these equations are time dependent.

Application to Lighting System Model

The basic principles presented here can be expanded to estimate the system reliability of the general lighting model presented in Appendix A. Then, by defining system failure criteria, component failure processes, and system characteristics, this methodology can be applied to determining the reliability of specific lighting systems.

The procedure for determining the reliability of visual guidance lighting systems basically entails:

a. Determining the reliability function for each component

b. Combining the component reliabilities to determine the unit reliability, i.e., the probability that a single light in the system is operational

c. Determining the system reliability based on unit reliability, system geometry, and system failure criteria.

Figure B6 illustrates the interconnection of components used in determining system reliability from the general lighting model.

The resultant system reliability (R_S) is the mean instantaneous, steady-state reliability; that is, the value of R_S is time independent. As described in Appendix A, after a period of operation, a maintained lighting system reaches a steady state in which the component reliability can be at any point in the reliability function with equal probability. Thus, a mean unit reliability can be determined after sufficient iterations using randomly selected component reliabilities. By iterating through this procedure, the mean system reliability can be determined for the steady state. The steps in this procedure are discussed in the following sections.

Determination of Component Reliability

The reliability function for each type of component (R_{Ci}) in the general lighting system can be estimated using Eq B2. However, the failure rate term (λ) must be determined to account for random failures of the equipment and the operation and maintenance policies under which the system functions. Eq B6 was derived from an evaluation of the factors influencing component reliability.

$$R_{ci}(t) \begin{cases} = e^{\frac{-(t-t_s)^{c_m}}{c_f}} & \text{for } t_r \geq t > t_s \\ = 1 & \text{for } t \leq t_s \end{cases} \qquad \text{[Eq B6]}$$

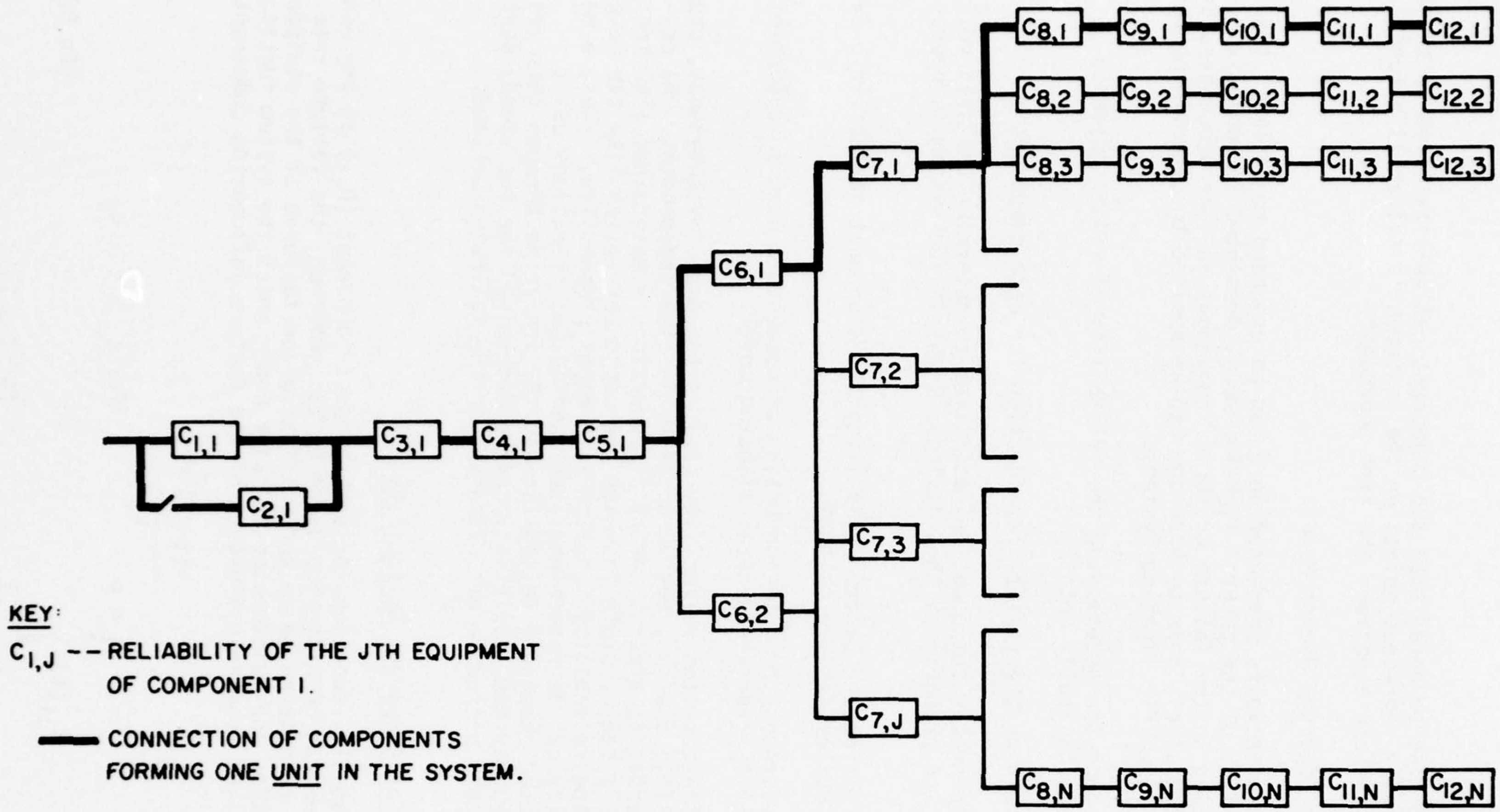


Figure B6. General reliability model.

where $R_{ci}(t)$ = the reliability of the ith component at operating time t

t = time of the reliability estimate

c_f = the failure coefficient

c_m = the maintenance coefficient

t_s = the safety time (i.e., the time after installation, $t = 0$, during which the possibility of the component failing is known to be zero)

t_r = the replacement time (i.e., the estimated time period in which the component is expected to be in service).

Description of each variable and procedures for estimating them are given below.

The Failure Coefficient (C_f)

The failure coefficient provides a measure of the random failure rate* of the component due to all failure mechanisms. Thus, for the lamp component, this variable accounts for failure by burn-out, breakage, vandalism, intensity decrease, or any other mechanism.

The failure coefficient for each component (C_{fi}) can be computed from Eq B7.

$$C_{fi} = \left(\frac{\text{total no. of component i in the system}}{\text{no. of component i failures per year}}\right) 50{,}000 \qquad \text{[Eq B7]}$$

In this relationship, 50,000 is a constant which provides the proper magnitude to the failure coefficient for use with the reliability function of Eq B6.

The total number of component i equipment in the system is determined from the geometry of the system being analyzed. For example, the system may have one commercial power source, three regulators, 150 lamps, etc.

The number of failures per year for each component can be determined from past records, data from a similar system in a similar environment, or engineering judgment. It should be noted that using judgment rather than empirical data decreases the confidence in the analytical precision.

---

*As used here, random failures are random with respect to time of occurrence. Failures due to unassignable causes are not considered to be random. Only by assuming that all failures have a cause (regardless of whether the cause is presently known) can the failure rate be analyzed with the aim of reducing it to a tolerable level.

The Maintenance Coefficient (C_m)

Figure B7 shows a two-lamp system in which one outage is allowed but two outages constitute system failure. System failure occurred when lamps 1 and 2 failed at the same time. Had the downtime (time when the equipment is inoperable due to failure) for lamp 1 been decreased to a point preceding the failure of lamp 2, the system would not have failed. Thus, the component downtime has a direct effect on the system's reliability.

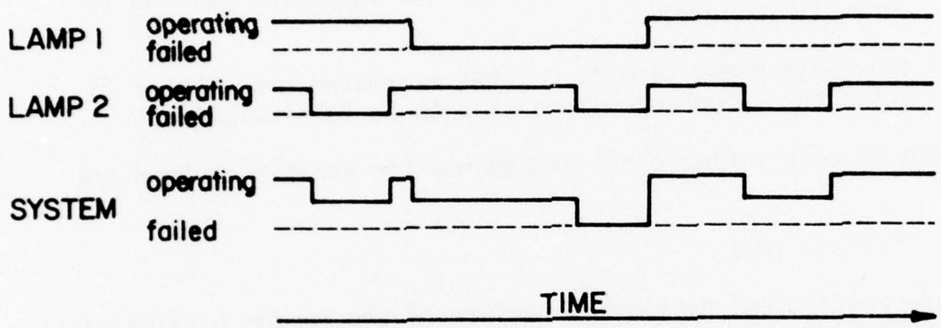


Figure B7. Failure of a two-lamp system.

The downtime is reflected in the component reliability function, since reliability is by definition a function of the number of equipment items out of the total equipment in the system operating at a given time (Eq B1).

When a component fails, four points in time determine the downtime:

T_f = the time at which failure occurs

T_d = the time at which the failure is detected

T_o = the time at which the system is taken out of service due to failures

T_c = the time at which the failure is corrected or repaired.

Figure B8 illustrates these points in time.

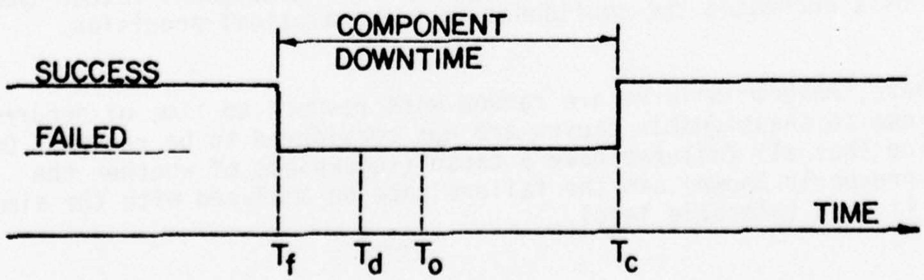


Figure B8. Time periods determining downtime.

The component downtime (T_D) is equal to $T_O - T_f$. However, if the system is not taken out of service by a single component failure, then T_D equals $T_c - T_f$. In either case, the downtime is composed of two periods: time from failure to detection, and time from detection to repair or system shutdown.

The detection time for critical components such as the commercial power can be nearly instantaneous. However, for other components, such as lamps, lenses, etc., the detection time depends on the frequency of performance inspections.

After failure detection, the remaining downtime is a function of the time necessary to repair or replace the component (included in this period is the time to troubleshoot the failure). This period is a function of maintenance (staff available, parts in stock, accessibility to the equipment, etc.). When the system is taken out of service, the downtime after detection is determined by the time required to relieve the system of aircraft requiring its guidance.

Since the downtime is a direct function of maintenance (inspection intervals and repair time), a maintenance coefficient was introduced to adjust the component reliability function based on the level of system maintenance. The maintenance coefficient is computed from

$$C_{mi} = \frac{\ln(-C_{fi} \ln R)}{\ln\{(t_L - t_s)/2\}} \qquad \text{[Eq B8]}$$

where C_{mi} = the maintenance coefficient for the ith component

C_{fi} = the failure coefficient for the ith component

t_L = the component's design life

t_s = the component's safety time

R = the average component reliability = $1 - (\frac{N_f}{N_o})(\frac{T_D}{T})$

where N_f = number of component failures per year

N_o = number of component i in the system

T_D = average downtime (hours)

T = time per year that component is expected to be operational (hours).

Since the level of preventive maintenance practiced on the system is reflected in the number of failures (N_f), the maintenance coefficient also accounts for preventive maintenance.

Safety Time (t_s)

The safety time is the period of time following installation during which there is no chance of the component failing (i.e., R(t) equals 1.0). This period of time can be estimated from empirical failure data or manufacturer's reliability data. If this type of information is not available, the safety time should be assumed to be zero; that is, the component has a possibility of failing at any time following installation.

Replacement Time (t_r)

The replacement time is the period of time during which the component is in service -- from installation (t equals 0) to replacement (t equals t_r). This period can be assumed to be the component's design life, unless the maintenance policy establishes a standard time of replacement. For example, if a group relampment policy is enforced at 80 percent of the design life of lamps rated at 500 hours, the replacement time would be 400 hours.

Determination of Unit Reliability

Unit reliability (R_u) is defined as the probability that a randomly chosen single unit in a system will be operational when called upon to perform. The unit is composed of one of each component type in the system. For the general airfield lighting system, the unit is one branch of the system, from commercial power through the lamp (see Figure B6).

Thus, the unit is a series system with one standby redundant component; its reliability can be determined using Eq B4. Since each component reliability is actually a function of time, Eq B4 can be written as:

$$R_u = \left\{1 - [1-R_1(t_1)][1-R_2(t_2)]\right\} \cdot R_3(t_3) \cdot R_4(t_4) \cdot R_5(t_5) \cdot R_6(t_6) \cdot R_7(t_7) \cdot R_8(t_8) \cdot R_9(t_9) \cdot R_{10}(t_{10}) \cdot R_{11}(t_{11}) \cdot R_{12}(t_{12}) \qquad \text{[Eq B9]}$$

In determining unit reliability, the following factors must be considered:

a. Each component's reliability is represented by a reliability distribution over time rather than being a constant.

b. The system is assumed to be in a steady-state condition, i.e., at any given time, a selected component may be at any point in its design life with equal probability.

c. The system geometry (the number of each component type) will influence the unit reliability.

A Monte Carlo simulation routine was used to account for these factors in the computation of unit reliability. Figure B9 illustrates this procedure.

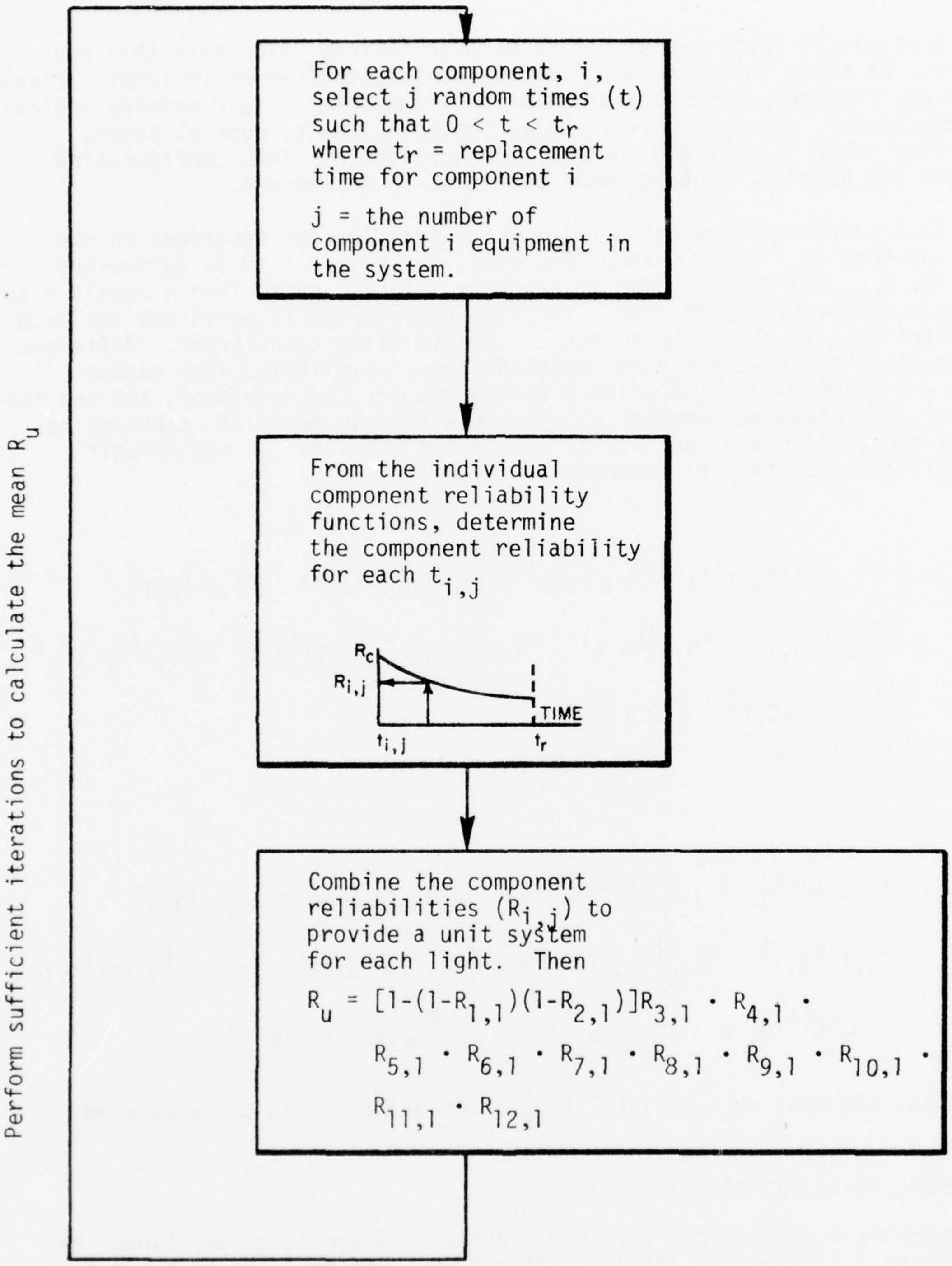


Figure B9. R_u calculation procedure.

A simple 16-light system can be used to further illustrate this procedure. As shown in Figure B10, the system is comprised of 16 lamps, lenses, fixtures, secondary cables, and isolating transformers; four primary cables; two regulators; and one control vault, control circuit, control panel, auxiliary power source, and commercial power source. This configuration follows the general lighting model presented in Appendix A.

Each component type has a reliability function, as described in the previous section. For the lamp component, the reliability is determined from the $R_{Lamp}(t)$ function for 16 randomly selected times from t equals 0 to t equals lamp replacement time. The same computation is performed for each component type in the circuit back to the isolating transformer. Different random times are used for each component type. Similarly, four random times are selected for the primary cable, two for the regulator, and one for each of the remaining components. The result is an array of component reliabilities which is a function of the system geometry. A set of unit reliabilities can then be computed as follows:

$$R_{u,1} = \left\{1 - [1-R_{1,1}(t_{1,1})][1-R_{2,1}(t_{2,1})]\right\} R_{3,1}(t_{3,1}) \cdot R_{4,1}(t_{4,1}) \cdot$$

$$R_{5,1}(t_{5,1}) \cdot R_{6,1}(t_{6,1}) \cdot R_{7,1}(t_{7,1}) \cdot R_{8,1}(t_{8,1}) \cdot R_{9,1}(t_{9,1}) \cdot$$

$$R_{10,1}(t_{10,1}) \cdot R_{12,1}(t_{12,1})$$

$$\vdots \qquad\qquad \vdots \qquad\qquad \vdots$$

$$R_{u,16} = \left\{1 - [1-R_{1,1}(t_{1,1})][1-R_{2,1}(t_{2,1})]\right\} R_{3,1}(t_{3,1}) \cdot R_{4,1}(t_{4,1}) \cdot$$

$$R_{5,1}(t_{5,1}) \cdot R_{6,2}(t_{6,2}) \cdot R_{7,4}(t_{7,4}) \cdot R_{8,16}(t_{8,16}) \cdot R_{9,16}(t_{9,16}) \cdot$$

$$R_{10,16}(t_{10,16}) \cdot R_{11,16}(t_{11,16}) \cdot R_{12,16}(t_{12,16})$$

From this, the mean unit reliability and its variance can be calculated.

Determination of System Reliability

Appendix A categorizes airfield lighting systems as either linear or bar systems. Because the failure criteria are different for each category, the procedure for determining the system reliability also differs.

Linear System Reliability

A linear system can be considered as a parallel redundant configuration of n units (lights). The mean unit reliability from the preceding

$R_{1,1}$ $R_{3,1}$ $R_{4,1}$ $R_{5,1}$

$R_{2,1}$

$R_{5,1}$: $R_{6,1}$, $R_{6,2}$

$R_{6,1}$: $R_{7,1}$, $R_{7,2}$

$R_{6,2}$: $R_{7,3}$, $R_{7,4}$

$R_{7,1}$	$R_{8,1}$	$R_{9,1}$	$R_{10,1}$	$R_{11,1}$	$R_{12,1}$
	$R_{8,2}$	$R_{9,2}$	$R_{10,2}$	$R_{11,2}$	$R_{12,2}$
	$R_{8,3}$	$R_{9,3}$	$R_{10,3}$	$R_{11,3}$	$R_{12,3}$
	$R_{8,4}$	$R_{9,4}$	$R_{10,4}$	$R_{11,4}$	$R_{12,4}$
$R_{7,2}$	$R_{8,5}$	$R_{9,5}$	$R_{10,5}$	$R_{11,5}$	$R_{12,5}$
	$R_{8,6}$	$R_{9,6}$	$R_{10,6}$	$R_{11,6}$	$R_{12,6}$
	$R_{8,7}$	$R_{9,7}$	$R_{10,7}$	$R_{11,7}$	$R_{12,7}$
	$R_{8,8}$	$R_{9,8}$	$R_{10,8}$	$R_{11,8}$	$R_{12,8}$
$R_{7,3}$	$R_{8,9}$	$R_{9,9}$	$R_{10,9}$	$R_{11,9}$	$R_{12,9}$
	$R_{8,10}$	$R_{9,10}$	$R_{10,10}$	$R_{11,10}$	$R_{12,10}$
	$R_{8,11}$	$R_{9,11}$	$R_{10,11}$	$R_{11,11}$	$R_{12,11}$
	$R_{8,12}$	$R_{9,12}$	$R_{10,12}$	$R_{11,12}$	$R_{12,12}$
$R_{7,4}$	$R_{8,13}$	$R_{9,13}$	$R_{10,13}$	$R_{11,13}$	$R_{12,13}$
	$R_{8,14}$	$R_{9,14}$	$R_{10,14}$	$R_{11,14}$	$R_{12,14}$
	$R_{8,15}$	$R_{9,15}$	$R_{10,15}$	$R_{11,15}$	$R_{12,15}$
	$R_{8,16}$	$R_{9,16}$	$R_{10,16}$	$R_{11,16}$	$R_{12,16}$

Note: $R_{i,j}$ is the reliability of the jth equipment of component i at the randomly selected time $t_{i,j}$.

Figure B10. Unit reliability illustration.

section can be used to represent the steady-state reliability of each light. If the system were considered failed only when all the lights failed, the system reliability (R_s) would be:

$$R_s = 1 - (1-R_u)^n \qquad \text{[Eq B10]}$$

However, one failure criterion for linear systems stipulates the percentage of random outages which constitutes system failure. For this criterion, the system reliability conforms to the binomial distribution or

$$R_s = \sum_{i=0}^{NR} \binom{n}{i} R_u^{n-i} (1-R_u)^i \qquad \text{[Eq B11]}$$

where i = the number of failures in the system

n = the total number of lights in the system

NR = the number of random failures allowed in the system (NR+1 would be the failure criterion)

R_u = unit reliability (the probability that a single typical light will be operational)

$\binom{n}{i}$ = the number of ways that i outages can be randomly distributed in n lights with the system not being in a failed state, or the factorial expansion of n elements taken i at a time $\left(\frac{n!}{i!(n-i)!}\right)$.

The second failure criterion for the linear system stipulates the number of consecutive light outages which constitute system failure. Thus, system reliability is a function of both the number of outages and their location. Based on the combined failure criteria, the reliability of a linear system can be expressed as:

$$R_s = \sum_{i=0}^{NR} W_i R_u^{n-i} (1-R_u)^i \qquad \text{[Eq B12]}$$

where W_i = the number of ways that i outages can be distributed among n lights with the system remaining in a success state.

An a priori proof of Eq B12 follows. By definition R_s is the probability of the system being in a success state, or

$$R_s = \sum_{i=0}^{n} \text{(Probability of i outages occurring with the system in a success state)}$$

The failure criteria which determine if the system is in a success state involve the maximum number of consecutive failures allowed (NC) and the maximum number of random failures allowed (NR).

The failure criteria result in the following conditions:

when i = 0,..., NC, the system is always in a success state

when i = NC+1,..., NR, the system is sometimes in a success state

when i = NR+1,..., n, the system is never in a success state.

Thus, the locations of the i outages must be considered in determining the probability of system success when i equals NC+1,..., NR. The system reliability can then be expressed as:

$$R_s = \sum_{i=0}^{n} W_i \cdot \text{probability of the i outages occurring in a specific sequence.}$$

If the probability of a lamp being in a success state is R_u, then the probability of i outages occurring in n lamps is $R_u^{n-i}(1-R_u)^i$ and, considering consecutiveness, the system reliability becomes:

$$R_s = \sum_{i=0}^{n} W_i \cdot R_u^{n-i}(1-R_u)^i$$

Note that when i exceeds the random outage failure criteria (NR), then W_i equals 0.

The following example illustrates this model. The example involves finding the system reliability for a three-lamp system (n=3) with system failure defined as all three lamps out <u>or</u> two consecutive lamps out. The probability of a lamp being on is R_u. Table B1 shows the eight possible conditions in which this system can be; three are failures and five are successes.

Table B1

Possible Conditions for Example

	S	S	S	S	F	S	F	F
Lamp 1	0	x	0	0	x	x	0	x
Lamp 2	0	0	x	0	x	0	x	x
Lamp 3	0	0	0	x	0	x	x	x
	i = 0	i = 1			i = 2			i = 3
	W_i = 1	W_i = 3			W_i = 1			W_i = 0

S = Success

F = Failure

0 = Light operating

x = Light failed

The system reliability is

$$R_s = \sum_{i=o}^{n} W_i R_u^{n-i} (1-R_u)^i$$

$$R_s = 1R_u^{3-0}(1-R_u)^0 + 3R_u^{3-1}(1-R_u)^1 + 1R_u^{3-2}(1-R_u)^2 + 0R_u^{3-3}(1-R_u)^3$$

Thus the reliability of any linear system can be determined from Eq B12 if R_u and W_i are known. Determination of R_u was described in the previous section. For linear systems, W_i is a multivariate integer function of n, NC, and i. For each (n, NC, i) there is a unique constant which is defined here as the consecutive coefficient, C(n,NC,i). (Appendix C describes the derivation of the consecutive coefficient.) Substituting the consecutive coefficient for W_i in Eq B12 gives the final form of the equation used to determine reliability of linear lighting systems.

$$R_s = \sum_{i=o}^{NR} C(n,NC,i) R_u^{n-1} (1-R_u)^i \qquad \text{[Eq B13]}$$

Bar System Reliability

Determination of the reliability of a bar system is an extension of the method for determining linear system reliability. Thus, bar system reliability is also a function of R_u and W_i and conforms to Eq B12. However, the number of ways i outages can be distributed in a bar system without system failure (W_i) must be determined in accordance with failure criteria for bar systems. These failure criteria stipulate the number of random outages allowed (NR), the number of consecutive bar failures allowed (NC), and the number of outages in a bar which constitutes failure of the bar (FB). Accounting for all these criteria makes determination of W_i quite complex.

For each i outages, where i equals 0 to NR, the outages are distributed between failed and nonfailed bars. This can be expressed as

$$W_i = \sum_{IB=MIN}^{MAX} NW(IB,i) \qquad \text{[Eq B14]}$$

where IB = the number of failed bars in the system

MIN = the minimum number of possible bar failures assuming i outages

MAX = the maximum number of possible bar failures assuming i outages

i = the number of lamp outages in the system

$NW(IB,i)$ = the number of ways that the system can be in a success state assuming IB bar failures and i total outages.

For each assumed IB between MIN and MAX, a range of the number of outages in the failed bars will satisfy each IB assumption. This range will be from (FB)(IB) to (NLB)(IB), where NLB is the number of lights in a bar. In addition to the distribution of outages between failed and nonfailed bars, the possibility of an outage occurring at any location within a bar must also be considered. To account for all these interactions, the mathematical interpretation of NW(IB,i) is divided into four terms as follows:

$$NW(IB,i) = \sum_{IR=0}^{i} \underbrace{\binom{NB-IB}{IR}}_{1} \cdot \underbrace{NLB^{IR}}_{2} \cdot \underbrace{K}_{3} \cdot \underbrace{C(NB,NC,IB)}_{4} \qquad \text{[Eq B15]}$$

where IB = the number of bar failures in the system from MIN to MAX

i = the total number of outages in the system from 0 to NR

IR = the number of outages in nonfailed bars from 0 to i

NB = the total number of bars in the system

NLB = the number of lights in a bar

NC = the number of consecutive bar failures allowed in the system and where the four terms are interpreted as:

$\binom{NB-IB}{IR}$ = the number of ways the IR outages can be distributed among the NB-IB nonfailed bars, or the factorial expansion of NB-IB elements taken IR at a time

NLB^{IR} = the number of ways the IR outages can be distributed within bars having NLB lights, or NLB to the IR power

K = the number of ways that i-IR outages can be distributed in the failed bars, or

$$K = \prod_{IH=FB}^{NLB} \binom{NLB}{IH}^{J(IH)} \qquad \text{or}$$

the product of the factorial expansions of NLB elements taken IH at a time and raised to the J(IH) power where J(IH) is the number of failed bars with exactly IH outages in the bar.

C(NB,NC,IB) = the number of ways that IB failed bars can occur in NB total bars with no more than NC consecutive failed bars. This is the consecutive coefficient previously discussed.

Thus, NW(IB,i) is a complex function of the number of outages, the location of outages in the bar system, the location of outages within failed and nonfailed bars, and the consecutive bar failure criteria. The summation of the NW(IB,i) terms from MIN to MAX provides the total number of ways that i outages can occur in the system while remaining in the success state.

From Eqs B14 and B15, the bar system reliability can be expressed as:

$$R_s = \sum_{i=o}^{NR} W_i R_u^{n-i} (1-R_u)^i$$

$$R_s = \sum_{i=o}^{NR} \sum_{IB=MIN}^{MAX} NW(IB,i) R_u^{n-i} (1-R_u)^i$$

$$R_s = \sum_{i=o}^{NR} \sum_{IB=MIN}^{MAX} \sum_{IR=0}^{i} \binom{NB-IB}{IR} \cdot NLB^{IR} \cdot K \cdot C(NB,NC,IB) \cdot R_u^{n-i} \cdot (1-R_u)^i$$

[Eq B16]

Analyzing this expression efficiently requires use of a digital computer. The computerized procedure is discussed in Appendix D.

APPENDIX C:

THE CONSECUTIVE COEFFICIENT

Introduction

The reliability of an airfield lighting system is the probability that the system will be in a success state. The success state is defined by the system failure criteria, which stipulate the allowed number and location of outages in the system.

If the failure criteria only stipulated the number of outages, the system reliability would conform to the binomial distribution, which can be expressed as

$$R_S = \sum_{i=0}^{NR} \binom{n}{i} R_u^{n-i} (1-R_u)^i \qquad \text{[Eq C1]}$$

where R_S = system reliability

n = number of lights in the system

NR = number of outages allowed

i = number of outages

R_u = probability of a light being in a success state

$(1-R_u)$ = probability of a light being in a failed state

$\binom{n}{i}$ = the binomial coefficient.

The binomial coefficient represents the number of ways that i outages can be distributed in n lights while the system remains in the success state. In this case, since the system must be in either a success or a failed state when there are i outages, the binomial coefficient is

$$\frac{n!}{i!(n-i)!} .$$

The system reliability would then be the sum of the products of the number of ways i outages can occur in the system times the probability of i outages occurring over the range from i equals 0 (no outages) to i equals NR (the failure criterion).

However, failure criteria for airfield lighting systems also stipulate the manner in which outages may occur. This stipulation is typically given as the maximum number of consecutive outages allowed. Thus, for a given i outages, the system can either be in a success or a failed state depending on the location of the outages. This results in a total number of ways for

i outages to occur with the system in a success state which is less than (or in some cases equal to) the binomial coefficient.

Consequently, to account for the outage location failure criterion, a consecutive coefficient was derived to replace the binomial coefficient. The reliability function for an airfield lighting system can then be determined from

$$R_s = \sum_{i=o}^{NR} [C(n,NC,i)R_u^{n-i}(1-R_u)^i] \qquad \text{[Eq C2]}$$

where $C(n,NC,i)$ = the consecutive coefficient for i outages in an n-lamp system where not more than NC consecutive outages can occur.

Derivation of the Consecutive Coefficient

The consecutive coefficient, $C(n,NC,i)$, is an integer function of the number of lights (n), the consecutive outages allowed (NC), and the total number of outages in the system (i). This coefficient is the number of ways that i outages can be distributed in n linearly aligned lights without having more than NC consecutive outages.

The consecutive coefficient has been found to be a recursive function which can be expressed by

$$\begin{aligned} C(n,NC,i) = {} & C(n-1,NC,i) + \\ & C(n-1,NC,i-1) - \\ & C(n-NC-2,NC,i-NC-1) \end{aligned} \qquad \text{[Eq C3]}$$

Using this relationship, the consecutive coefficients can be derived for any set of (n,NC,i) starting with the following intuitive properties:

a. $C(n,NC,i) = 0$ if $n < i$

b. $C(n,NC,i) = \binom{n}{i}$, the binomial coefficient, if $NC \geq i$

c. $C(n,NC,i) = 0$ if $n = i$ and $NC < i$

d. $C(n,NC,i) = 1$ if $n = NC = i$

Figure C1 shows the program listing for a computerized procedure developed to calculate the consecutive coefficients. The program is written in PASCAL computer code, since FORTRAN does not directly allow for recursive calculations.

Figure C2 shows a sample of consecutive coefficients. Note that $C(3,1,1) = 3$; i.e., one outage (i) can occur in a three-lamp system (n)

```
PROGRAM  CONSECT(INPUT,OUTPUT.TAPE3)  ;
TYPE  MAT=ARRAY¢-5..150, 1.. 5,-5..30! OF REAL;
      VCT=ARRAY¢1..150! OF REAL;
VAR   I,N,K,J:INTEGER;
      TAPE3:TEXT;
      IT,IX,IP    :INTEGER;
      NN,NI:INTEGER;
      FACTRL:VCT;
      C:MAT;
      R,T:REAL;
      P,S:REAL;
FUNCTION A(N,K,J:INTEGER):REAL;
VAR   B:REAL;
BEGIN
      IF C¢N,K,J!>-1 THEN B:=C¢N,K,J!
      ELSE  IF J<=0  THEN B:=1.0
      ELSE  IF(N=J) AND (K>=J) THEN B:=1.0
      ELSE  IF(N=J) AND (K<J)  THEN B:=0.0
      ELSE  IF (J> N) OR (K<=0) THEN B:=0.0
      ELSE  IF K>=J THEN B:=FACTRL¢N!/(FACTRL¢J!*FACTRL¢N-J!)
      ELSE  B:=A(N-1,K,J)+A(N-1,K,J-1)-A(N-K-2,K,J-K-1);
      A:=B;
      IF  (N>0)AND(K>0)AND(J>0)  THEN C¢N,K,J!:=B;
END;
BEGIN
      FOR I:=1 TO 150 DO
      BEGIN
      FACTRL¢I!:=1;
      FOR J:=1 TO I  DO  FACTRL¢I!:=FACTRL¢I!*J;
      END;
      FOR N:=-2 TO 150 DO BEGIN
      FOR K:=1 TO 5 DO BEGIN
      FOR J:=-2 TO 30  DO
      C¢N,K,J!:=-2;
      END;
      END;
      LINELIMIT(OUTPUT,150*10*20):
      FOR K:=1 TO 2 DO BEGIN
      FOR  N:=1 TO 36 DO    BEGIN
      NN:=(N+1) DIV (2) ;
      FOR J:=1 TO NN DO BEGIN
      WRITE(TAPE3 ,N,K,J,A(N,K,J));
      WRITELN(TAPE3 );
      END;
      END;
      END;
      FOR K:=1 TO 3 DO BEGIN
      FOR N:=40 TO 150 DO BEGIN
      NI:=(N) DIV ( 5);
      FOR J:=1 TO NI DO BEGIN
      WRITE(OUTPUT,N,K,J,A(N,K,J));
      END;
      END;
      END;
END.
```

Figure C1. Consecutive coefficient program listing.

n	NC	i	C(n,NC,i)	n	NC	i	C(n,NC,i)	n	NC	i	C(n,NC,i)
1	1	1	.1000000000E+01	2	1	1	.2000000000E+01	3	1	1	.3000000000E+01
3	1	2	.1000000000E+01	4	1	1	.4000000000E+01	4	1	2	.3000000000E+01
5	1	1	.5000000000E+01	5	1	2	.6000000000E+01	5	1	3	.1000000000E+01
6	1	1	.6000000000E+01	6	1	2	.1000000000E+02	6	1	3	.4000000000E+01
7	1	1	.7000000000E+01	7	1	2	.1500000000E+02	7	1	3	.1000000000E+02
7	1	4	.1000000000E+01	8	1	1	.8000000000E+01	8	1	2	.2100000000E+02
8	1	3	.2000000000E+02	8	1	4	.5000000000E+01	9	1	1	.9000000000E+01
9	1	2	.2800000000E+02	9	1	3	.3500000000E+02	9	1	4	.1500000000E+02
9	1	5	.1000000000E+01	10	1	1	.1000000000E+02	10	1	2	.3600000000E+02
10	1	3	.5600000000E+02	10	1	4	.3500000000E+02	10	1	5	.6000000000E+01
11	1	1	.1100000000E+02	11	1	2	.4500000000E+02	11	1	3	.8400000000E+02
11	1	4	.7000000000E+02	11	1	5	.2100000000E+02	11	1	6	.1000000000E+01
12	1	1	.1200000000E+02	12	1	2	.5500000000E+02	12	1	3	.1200000000E+03
12	1	4	.1260000000E+03	12	1	5	.5600000000E+02	12	1	6	.7000000000E+01
13	1	1	.1300000000E+02	13	1	2	.6600000000E+02	13	1	3	.1650000000E+03
13	1	4	.2100000000E+03	13	1	5	.1260000000E+03	13	1	6	.2800000000E+02
13	1	7	.1000000000E+01	14	1	1	.1400000000E+02	14	1	2	.7800000000E+02
14	1	3	.2200000000E+03	14	1	4	.3300000000E+03	14	1	5	.2520000000E+03
14	1	6	.8400000000E+02	14	1	7	.8000000000E+01	15	1	1	.1500000000E+02
15	1	2	.9100000000E+02	15	1	3	.2860000000E+03	15	1	4	.4950000000E+03
15	1	5	.4620000000E+03	15	1	6	.2100000000E+03	15	1	7	.3600000000E+02
15	1	8	.1000000000E+01	16	1	1	.1600000000E+02	16	1	2	.1050000000E+03
16	1	3	.3640000000E+03	16	1	4	.7150000000E+03	16	1	5	.7920000000E+03
16	1	6	.4620000000E+03	16	1	7	.1200000000E+03	16	1	8	.9000000000E+01
17	1	1	.1700000000E+02	17	1	2	.1200000000E+03	17	1	3	.4550000000E+03
17	1	4	.1001000000E+04	17	1	5	.1287000000E+04	17	1	6	.9240000000E+03
17	1	7	.3300000000E+03	17	1	8	.4500000000E+02	17	1	9	.1000000000E+01
18	1	1	.1800000000E+02	18	1	2	.1360000000E+03	18	1	3	.5600000000E+03
18	1	4	.1365000000E+04	18	1	5	.2002000000E+04	18	1	6	.1716000000E+04
18	1	7	.7920000000E+03	18	1	8	.1650000000E+03	18	1	9	.1000000000E+02
19	1	1	.1900000000E+02	19	1	2	.1530000000E+03	19	1	3	.6800000000E+03
19	1	4	.1820000000E+04	19	1	5	.3003000000E+04	19	1	6	.3003000000E+04
19	1	7	.1716000000E+04	19	1	8	.4950000000E+03	19	1	9	.5500000000E+02
19	1	10	.1000000000E+01	20	1	1	.2000000000E+02	20	1	2	.1710000000E+03

Figure C2. Sample of consecutive coefficient data base.

n	NC	i	C(n,NC,i)	n	NC	i	C(n,NC,i)	n	NC	i	C(n,NC,i)
112	3	2	.6216000000E+04	112	3	3	.2279200000E+06	112	3	4	.6210711000E+07
112	3	5	.1341420480E+09	112	3	6	.2391789618E+10	112	3	7	.3620624998E+11
112	3	8	.4749283635E+12	112	3	9	.5482971157E+13	112	3	10	.5639693502E+14
112	3	11	.5219376045E+15	113	3	1	.1130000000E+03	113	3	2	.6328000000E+04
113	3	3	.2341360000E+06	113	3	4	.6438630000E+07	113	3	5	.1403526510E+09
113	3	6	.2525925888E+10	113	3	7	.3859783544E+11	113	3	8	.5111292544E+12
113	3	9	.5957788062E+13	113	3	10	.6187799317E+14	113	3	11	.5783066749E+15
114	3	1	.1140000000E+03	114	3	2	.6441000000E+04	114	3	3	.2404640000E+06
114	3	4	.6672765000E+07	114	3	5	.1467911720E+09	114	3	6	.2666272653E+10
114	3	7	.4112355139E+11	114	3	8	.5497215267E+12	114	3	9	.6468800499E+13
114	3	10	.6783375678E+14	114	3	11	.6401548906E+15	115	3	1	.1150000000E+03
115	3	2	.6555000000E+04	115	3	3	.2469050000E+06	115	3	4	.6913228000E+07
115	3	5	.1534638270E+09	115	3	6	.2813057830E+10	115	3	7	.4378960823E+11
115	3	8	.5908393050E+12	115	3	9	.7018399646E+13	115	3	10	.7430041601E+14
115	3	11	.7079568456E+15	116	3	1	.1160000000E+03	116	3	2	.6670000000E+04
116	3	3	.2534600000E+06	116	3	4	.7160132000E+07	116	3	5	.1603769440E+09
116	3	6	.2966515552E+10	116	3	7	.4660244424E+11	116	3	8	.6346229244E+12
116	3	9	.7609110798E+13	116	3	10	.8131655201E+14	116	3	11	.7822233188E+15
117	3	1	.1170000000E+03	117	3	2	.6786000000E+04	117	3	3	.2601300000E+06
117	3	4	.7413591000E+07	117	3	5	.1675369640E+09	117	3	6	.3126886280E+10
117	3	7	.4956873187E+11	117	3	8	.6812191579E+12	117	3	9	.8243599580E+13
117	3	10	.8892327102E+14	117	3	11	.8635036646E+15	118	3	1	.1180000000E+03
118	3	2	.6903000000E+04	118	3	3	.2669160000E+06	118	3	4	.7673720000E+07
118	3	5	.1749504420E+09	118	3	6	.3294416916E+10	118	3	7	.5269538402E+11
118	3	8	.7307814511E+12	118	3	9	.8924678385E+13	118	3	10	.9716434467E+14
118	3	11	.9523883378E+15	119	3	1	.1190000000E+03	119	3	2	.7021000000E+04
119	3	3	.2738190000E+06	119	3	4	.7940635000E+07	119	3	5	.1826240480E+09
119	3	6	.3469360917E+10	119	3	7	.5598956047E+11	119	3	8	.7834701624E+12
119	3	9	.9655313045E+13	119	3	10	.1060863568E+15	119	3	11	.1049511559E+16
120	3	1	.1200000000E+03	120	3	2	.7140000000E+04	120	3	3	.2808400000E+06
120	3	4	.8214453000E+07	120	3	5	.1905645680E+09	120	3	6	.3651978410E+10
120	3	7	.5945867448E+11	120	3	8	.8394528096E+12	120	3	9	.1043862974E+14
120	3	10	.1157388568E+15	120	3	11	.1155554126E+16	120	3	12	.1047364843E+17

Figure C2 (cont'd).

without more than one consecutive outage (NC) in exactly three ways. As another example, C(112,3,2) = 6216; i.e., two outages can occur in a 112-lamp system without more than three consecutive outages in exactly 6216 ways.

Figure C3 illustrates the effect of considering consecutive outages in addition to the total number of outages. Curve 1 is the binomial coefficient, where consecutiveness is not considered. Curves 2, 3, 4, and 5 consider a failure criterion of 4, 3, 2, and 1 consecutive outages respectively. For the case of NC = 1 (curve 5), the system becomes failed when any two adjacent lights are out. For a given n, C(n,NC,i) approaches the binomial coefficient as NC increases. As n increases, all of the curves approach Curve 1. However, it should be noted that C(n,NC,i) is on a logarithmic scale and that although the divergence of the curves may appear small for large n's, the difference between coefficients is large.

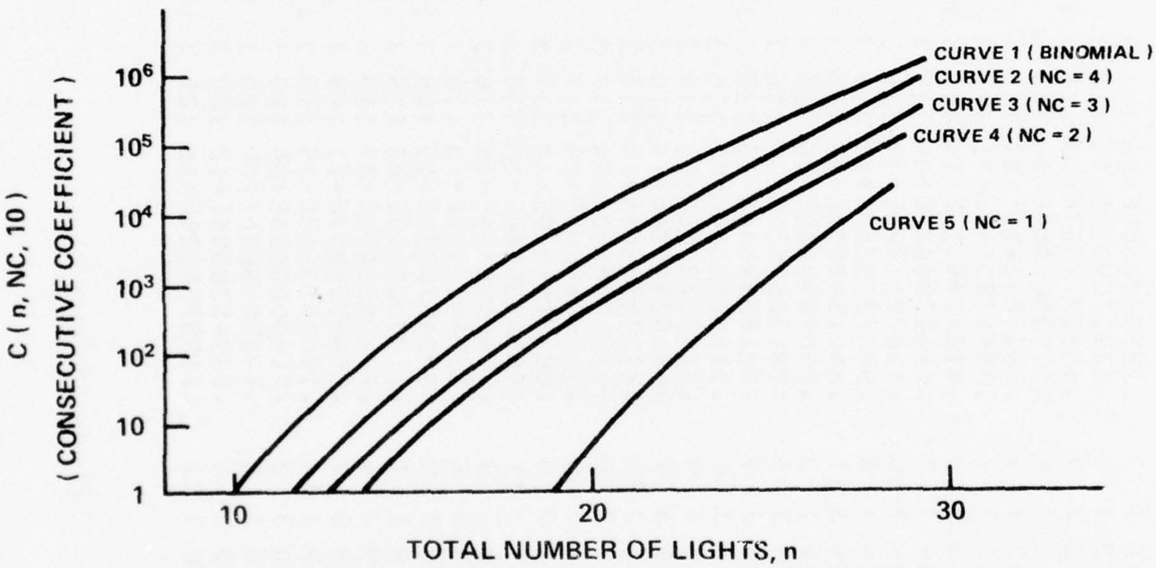


Figure C3. Comparison of binomial and consecutive coefficients.

Although defined for application to the analysis of airfield lighting system reliability, the consecutive coefficient can be applied to any problem in which the probability of consecutive events is significant. Further description of the derivation and use of the consecutive coefficient may be found elsewhere.[2]

[2]F. Kuo and E. S. Lindow, *Reliability Analysis of Airfield Lighting Systems*, paper prepared for presentation to the Twenty-second Conference on the Design of Experiments in Army RD&T, Adelphi, MD, 20 October 1976.

Implementation of the Consecutive Coefficient

The consecutive coefficient must be determined for each number of outages (i) up to the number allowed in the system (NR). Since the consecutive coefficient function is recursive, the computer time and memory, and therefore, the cost, of determining the coefficients become excessive. Thus, constructing a data base for the anticipated ranges of n, NC, and i becomes efficient. The coefficients required in an analysis can then be selected from the data base without incurring the computer time and expense for calculating them. Such a data base was constructed for use with the computerized procedure discussed in Appendix D. The data base includes consecutive coefficients for the following ranges: n from 1 to 150, NC from 1 to 5, and i from 0 to 20 percent of n. This data base is currently included with the program deck, and its operation is discussed in Appendix D.

APPENDIX D:

PROGRAM DOCUMENTATION

A computer program was developed to aid in evaluating the reliability of airfield visual guidance lighting systems. The program--Reliability Analysis of Airfield Lighting Systems (RAALS)--is designed to estimate the present steady-state reliability of any such lighting system. The program can evaluate all of the diverse lighting systems by using a general lighting system model and adapting it to a specific system through the selection of user input. Appendix A presents the general lighting system model and its components' characteristics. The reliability theory methodology employed in the program is discussed in Appendix B.

For further information on the development or use of the RAALS program, contact U.S. Army Construction Engineering Research Laboratory, Engineering and Materials Division, P. O. Box 4005, Champaign, IL 61820.

RAALS Program Logic

The RAALS program models the system reliability logic presented in Appendix B. Essentially, this entails

a. Determining component reliability functions

b. Estimating unit reliability through simulation

c. Calculating system reliability.

Figure D1 shows a simplified logical flow chart for the RAALS program. The procedure includes an exact solution to the number of possible states the system can be in while remaining operational and a stochastic solution for the possibility of each state occurring.

Program and Subroutine Functions

Table D1 lists and describes the program and subroutine functions included in RAALS.

RAALS Input Requirements

Table D2 lists input data cards required for the operation of the RAALS program. The table also describes the cards' format and content. Appendix B provides further explanation for determining appropriate values for the input variables.

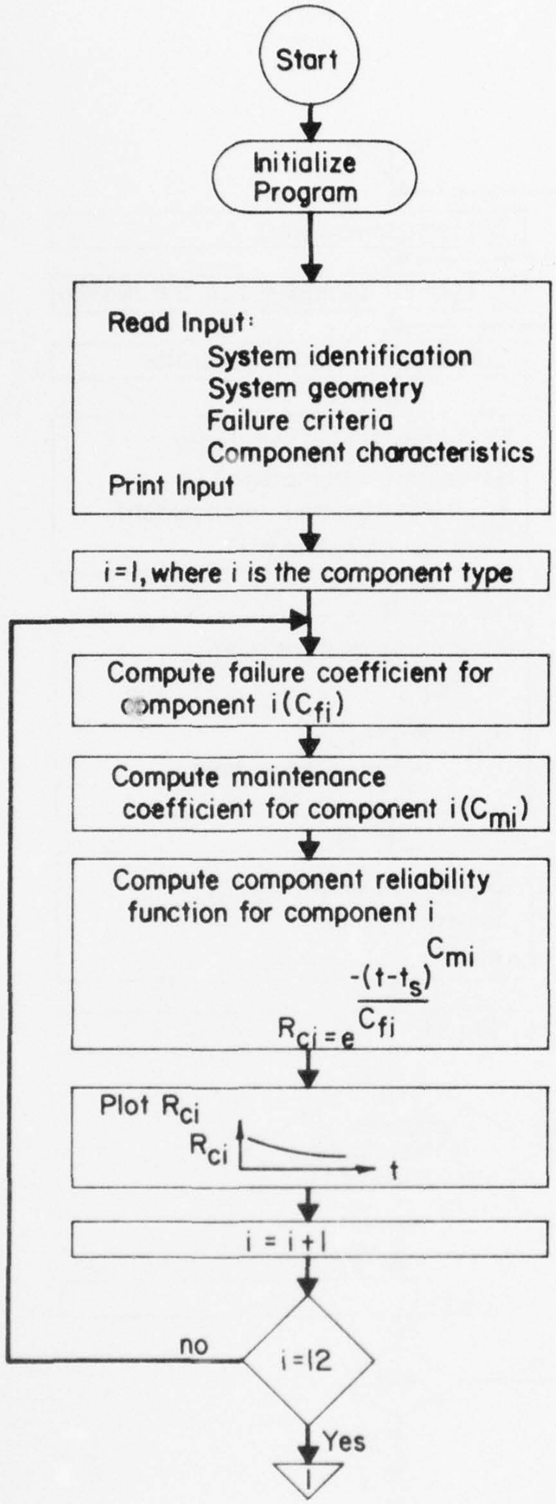


Figure D1. Simplified logical flow chart for RAALS program.

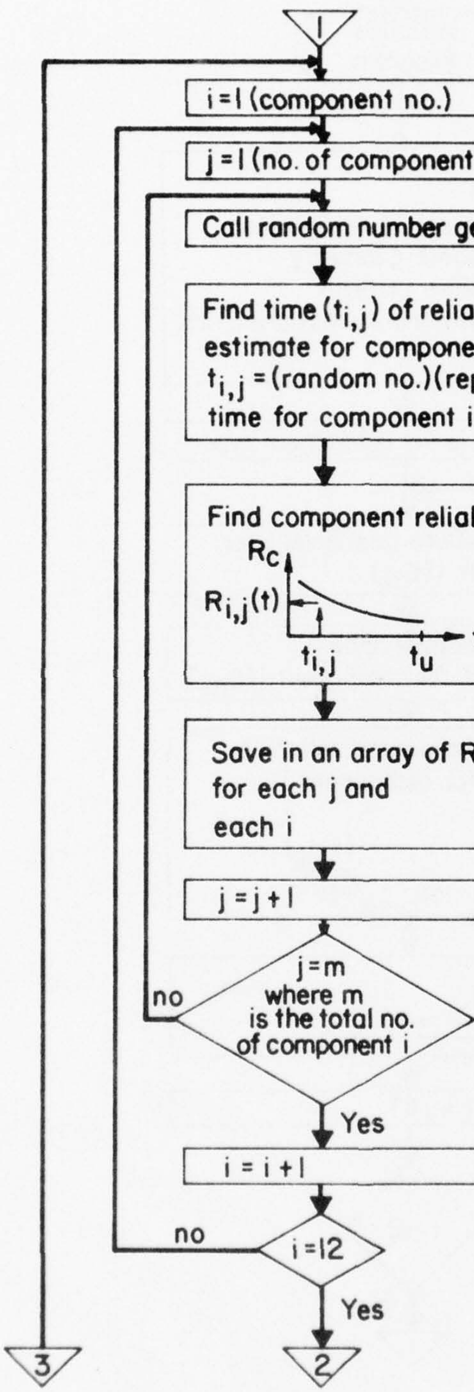


Figure D1 (cont'd).

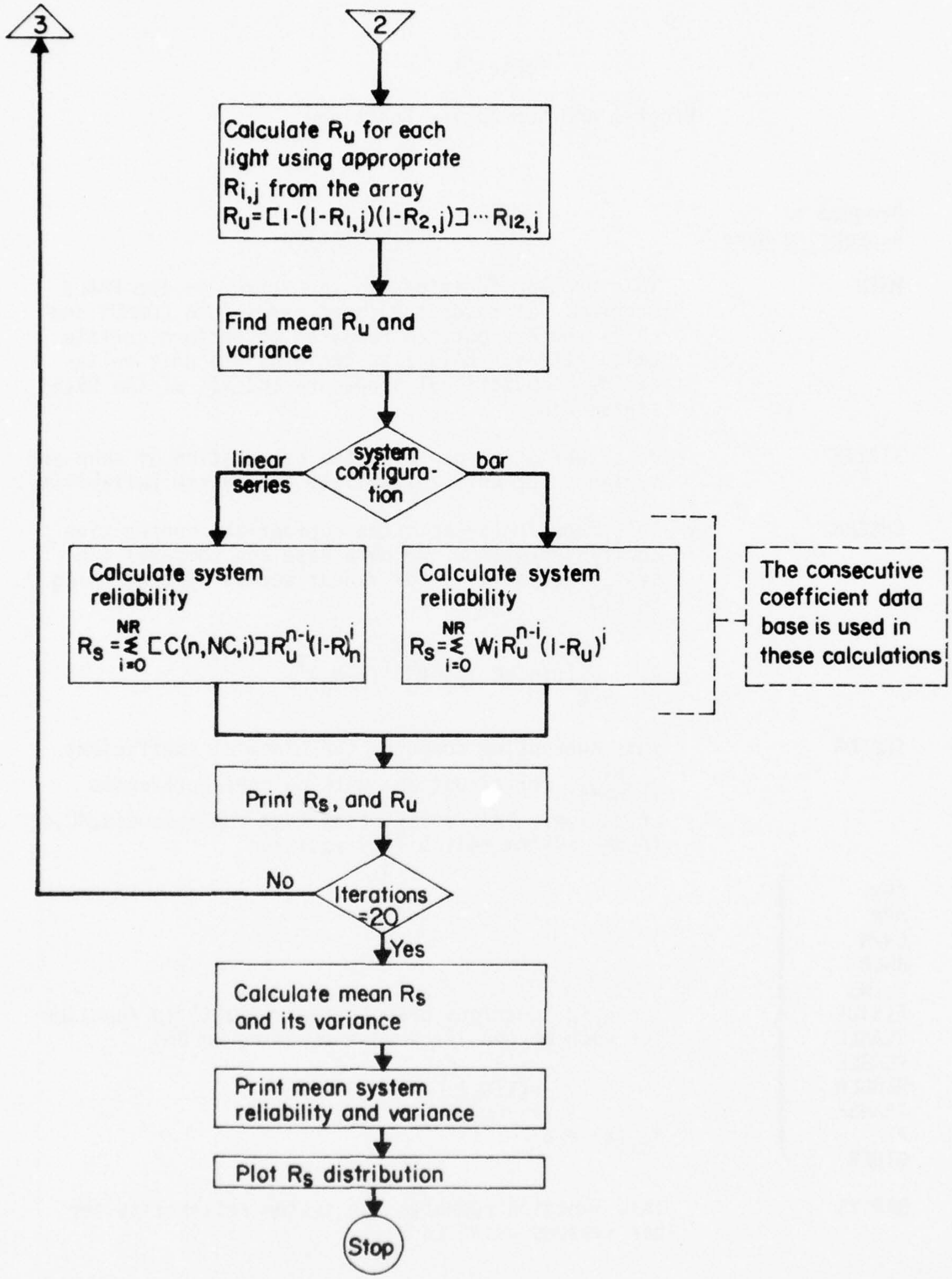


Figure D1 (cont'd).

Table D1

Program and Subroutine Functions

Program or Subroutine Name	Description
MAIN	This program functions as the driver in the RAALS program. It reads the input cards into COMMON and calls the subroutines required to perform certain calculations. MAIN also contains the unit reliability computational procedure and all of the PRINT statements.
STATIS	This subroutine performs the calculation of mean and variance for unit reliability and system reliability.
CNSCPB	This function selects the appropriate consecutive coefficients from the data base and computes the system reliability for linear series systems using Eq B13: $$R_s = \sum_{i=0}^{NR} [C(n,NC,i)]\ R_u^{n-i}(1-R_u)^i$$
FACTOR	This subroutine computes the binomial coefficient $\frac{n!}{i!(n-i)!}$ for situations with no consecutiveness criterion. This coefficient then replaces C(n,NC,i) in the system reliability equation.
CPW APW CNPN BULB XLENS FIXTUR SCABLE PCABLE REGULA TRANSF FI OTHER	These 12 functions compute the reliability function for each of the 12 components using Eq B6. $$R_{ci}(t) = e^{\frac{-(t-t_s)^{c_m}}{c_f}}$$
BARSYS	This function computes the system reliability for bar systems using Eq B16:

Table D1 (cont'd)

$$R_s = \sum_{i=o}^{NR} \sum_{IB=MIN}^{MAX} \sum_{IR=o}^{i} \binom{NB-IB}{IR} \cdot NLB^{IR} \cdot K \cdot$$

$$C(NB,NC,IB) \cdot R_u^{n-i} \cdot (1 - R_u)^i$$

STPLT 1	This subroutine is used to plot the component reliability functions and the distribution of system reliability.
RANF	This function is a random number generator between 0 and 1.0, exclusive.

Table D2

Input Data Cards for RAALS

Card Type	Columns	Format	Description
A	1-30	30A1	The geographic location or other identification title of the lighting system being analyzed consisting of up to 30 alpha-numeric characters.
B	1-17	17A1	The type and/or identification of the lighting system (e.g., ALSF-11, or R/W Centerline).
	18-20	3X	Blank
	21-30	F10.2	System failure criteria stipulating the percent of random outages constituting system failure. Entered as a percent.
	31-35	5X	Blank
	36-37	I2	System failure criteria stipulating the number of consecutive outages or consecutive bar failures constituting system failure. Entered as a right-justified integer.
	38-40	3X	Blank
	41-42	I2	Number of lamps in a light bar. For linear series systems (e.g., centerline) use 1. Entered as a right-justified integer.
C	1-10	F10.2	Average number of hours per day during which the system is operational.
	11-20	F10.2	Average number of days per year during which the system is operational.

Table D2 (cont'd)

Card Type	Columns	Format	Description
D-O			Card types D through O provide the characteristics of each component as follows: D -- Commercial power E -- Auxiliary power F -- Control panel G -- Control circuit H -- Control vault I -- Regulator J -- Primary cable K -- Isolating transformer L -- Secondary cable M -- Fixture N -- Lens O -- Lamp The information on each card consists of the following:
	1-5	I5	Number of this type component in the system. Entered as a right-justified integer.
	6-10	I5	Average number of failures per year for this component in this system. Entered as a right-justified integer.
	11-20	F10.2	Replacement time* for this component (hours).
	21-30	F10.2	Safety time* for this component (hours).
	31-40	F10.2	Average down-time* per failure for this component (hours).
	41-50	F10.2	Design life for this component (hours).
	51-80		This field is reserved for user comments. It is not read by the program.

*See Appendix B for definition of these terms.

RAALS Program Operation

The RAALS program is written in FORTRAN Extended for CDC 6000 series computers. It was developed using a CDC 6600 computer; with proper modifications, the program is adaptable to operation on other computer systems.

Figure D3 shows the deck setup for the CDC 6600 computer. The individual parts of the deck are described in Table D3.

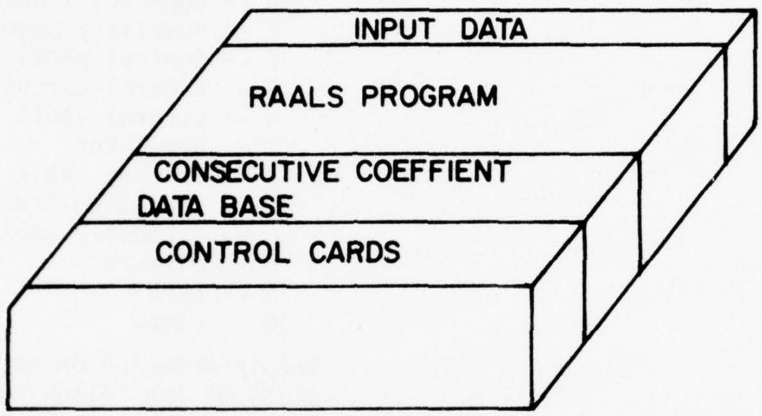


Figure D2. RAALS deck setup.

Example Problem

The centerline bars of a typical ALSF-II installation were selected to illustrate the use of the RAALS program. Figure D3 shows the input cards for the example. Table D4 provides an explanation of each input variable. The program output (Figure D4) includes a title page, input data listing, plots of each component reliability function, table of unit and system reliabilities for each of 20 program iterations, a plot of the system reliability distribution, and the mean system reliability and its variance.

The system reliability for this example is 0.996016 with a variance of 2.442×10^{-6}. Thus, the system is expected to be operational 99.6 percent of the time with a standard deviation of ± 0.16 percent. Since the variance of the system reliability estimates is small for these data, the resulting steady-state system reliability may be considered to be a good approximation of the availability expected from this system. A large variance, on the order of 10^{-1} or 10^{-2}, would indicate that the system contains at least one component whose reliability fluctuates widely. In this case, the plotted component reliability function should be examined to determine how the system reliability can be improved.

Table D3

RAALS Deck Setup

Type	Cards	Notes
Job Control	Job Card	Identifies the job and stipulates job parameters. A minimum of CM150000 and T200 is suggested.
	Charge Card	Cost accounting card (installation-dependent).
	COPYCR (Input, Consec)	Copies the Consecutive Coefficient Data Base from the INPUT file to the file CONSEC for program usage.
	FTN.	Compiles the RAALS program. Other parameters for compilation may be specified.
	LGO.	Loads and executes RAALS.
	7/8/9	End-of-Record card. 7,8,9 all punched in column one.
Consecutive Coefficient Data Base*		
	7/8/9	
RAALS Program*		
	7/8/9	
Input Deck	Card types A through O	The input deck consists of the 15 card types described in Table D2.
	6/7/8/9	End-of-Information card.

*The job control cards and the deck setup assume that all the information is on cards and the job is run on CDC 6000 series computers. If the RAALS program and data base are on a permanent file or magnetic tape, the job control cards and the deck setup would be changed.

DATE ____________ 80 COLUMN KEY PUNCH TRANSCRIPT LAYOUT SHEET SHEET OF SHEETS

```
EXAMPLE PROBLEM
ALSF-2 CENTERLINE   20.0            2    5
  12.0     365.0
    1    1  175000.     0.      24.      175000.           COMMERCIAL POWER
    1    1  175000.     0.      36.      175000.           AUXILIARY POWER
    1    1  175000.     0.      24.      175000.           CONTROL PANEL
    1    1  100000.     0.      24.      100000.           CONTROL CIRCUIT
    1    3  100000.     0.      12.      100000.           CONTROL VAULT
    3    2  175000.     0.      24.      175000.           REGULATOR
    3    3  100000.     0.      12.      100000.           PRIMARY CABLE
  150   15   60000.     0.      24.       60000.           ISOLATING TRANSFORMER
  150   40   60000.     0.      48.       60000.           SECONDARY CABLE
  150   25   60000.     0.      36.        0000.           FIXTURE
  150   75   40000.     0.      24.       40000.           LENS
  150  160    8000.     0.      24.       10000.           LAMP
```

CERL Form 128
20 April 1975

Figure D3. Example problem input data.

Table D4

Input for Example Problem

EXAMPLE PROBLEM

(An identification title for this problem.)

ALSF-2 CENTERLINE	20.0	2	5

(The system being analyzed is an ALSF-II with failure criteria of 20 percent outages and two consecutive bar failures in a bar system having five lamps per bar.)

12.0	365.

(The system operates an average of 12.0 hours per day, 365 days per year.)

1	1	175000.	0.	24.	175000.

(The commercial power component characteristics:

a. There is one commercial power component

b. It is estimated to fail once per year from past records

c. Since this component is not expected to be replaced during its design life, the replacement time is set at 175,000 hours (equivalent to a 20-year design life)

d. The safety time is zero, i.e., the component has a probability of failing any time after installation

e. From past records, it is estimated that this component requires an average of approximately 24 hours downtime per failure

f. The design life for this component is 20 years or 175,000 hours.)

1	1	175000.	0.	36.	175000.

(Auxiliary Power)

1	1	175000.	0.	24.	175000.

(Control Panel)

1	1	100000.	0.	24.	100000.

(Control Circuit)

Table D4 (cont'd)

1	3	100000.	0.	12.	100000.
(Control Vault Equipment)					
3	2	175000.	0.	24.	175000.
(Regulator)					
3	3	100000.	0.	12.	175000.
(Primary Cable)					
150	15	60000.	0.	24.	60000.
(Isolating Transformers)					
150	40	60000.	0.	48.	60000.
(Secondary Cables)					
150	25	60000.	0.	36.	60000.
(Fixtures)					
150	75	40000.	0.	24.	40000.
(Lenses)					
150	160	8000.	0.	24.	10000.

(Lamps -- Note: the replacement time for this component is based on group relampment at 80 percent of the design life. The design life of the lamp is 500 hours at maximum intensity; this converts to 10,000 hours real time.)

```
RELIABILITY ANALYSIS OF AIRFIELD LIGHTING SYSTEMS
-------------------------------------------------


          U.S. ARMY CORPS OF ENGINEERS
    CONSTRUCTION ENGINEERING RESEARCH LABORATORY
              CHAMPAIGN, ILLINOIS


             DATE:     09/09/76
```

Figure D4. Example problem output.

LOCATION: EXAMPLE PROBLEM SYSTEM TYPE: ALSF-2 CENTERLINE

COMPONENT CHARACTERISTICS

COMPONENT TYPE	NUMBER	FAILURES PER YEAR	REPLACEMENT TIME (HRS.)	SAFETY TIME (HRS.)	DOWN TIME (HRS.)	DESIGN LIFE (HRS.)	MAINTENANCE COEFFICIENT	FAILURE COEFFICIENT	AVERAGE COMPONENT RELIABILITY
COMMERCIAL POWER	1	1	175000.	0.	24.	175000.	.493504	50000.	.994521
AUXILIARY POWER	1	1	175000.	0.	36.	175000.	.529256	50000.	.991781
CONTROL PANEL	1	1	175000.	0.	24.	175000.	.493504	50000.	.994521
CABLE TO VAULT	1	1	100000.	0.	24.	100000.	.519029	50000.	.994521
CONTROL VAULT	1	3	100000.	0.	12.	100000.	.455089	16666.	.991781
REGULATOR	3	2	175000.	0.	24.	175000.	.493423	75000.	.996347
PRIMARY CABLE	3	3	100000.	0.	12.	100000.	.454839	50000.	.997260
TRANSFORMER	150	15	60000.	0.	24.	60000.	.544508	500000.	.999452
SECONDARY CABLE	150	40	60000.	0.	48.	60000.	.611860	187500.	.997078
FIXTURE	150	25	60000.	0.	36.	60000.	.583879	300000.	.998630
LENSES	150	75	40000.	0.	24.	40000.	.566911	100000.	.997260
LAMP	150	160	8000.	0.	24.	10000.	.659367	46875.	.994155

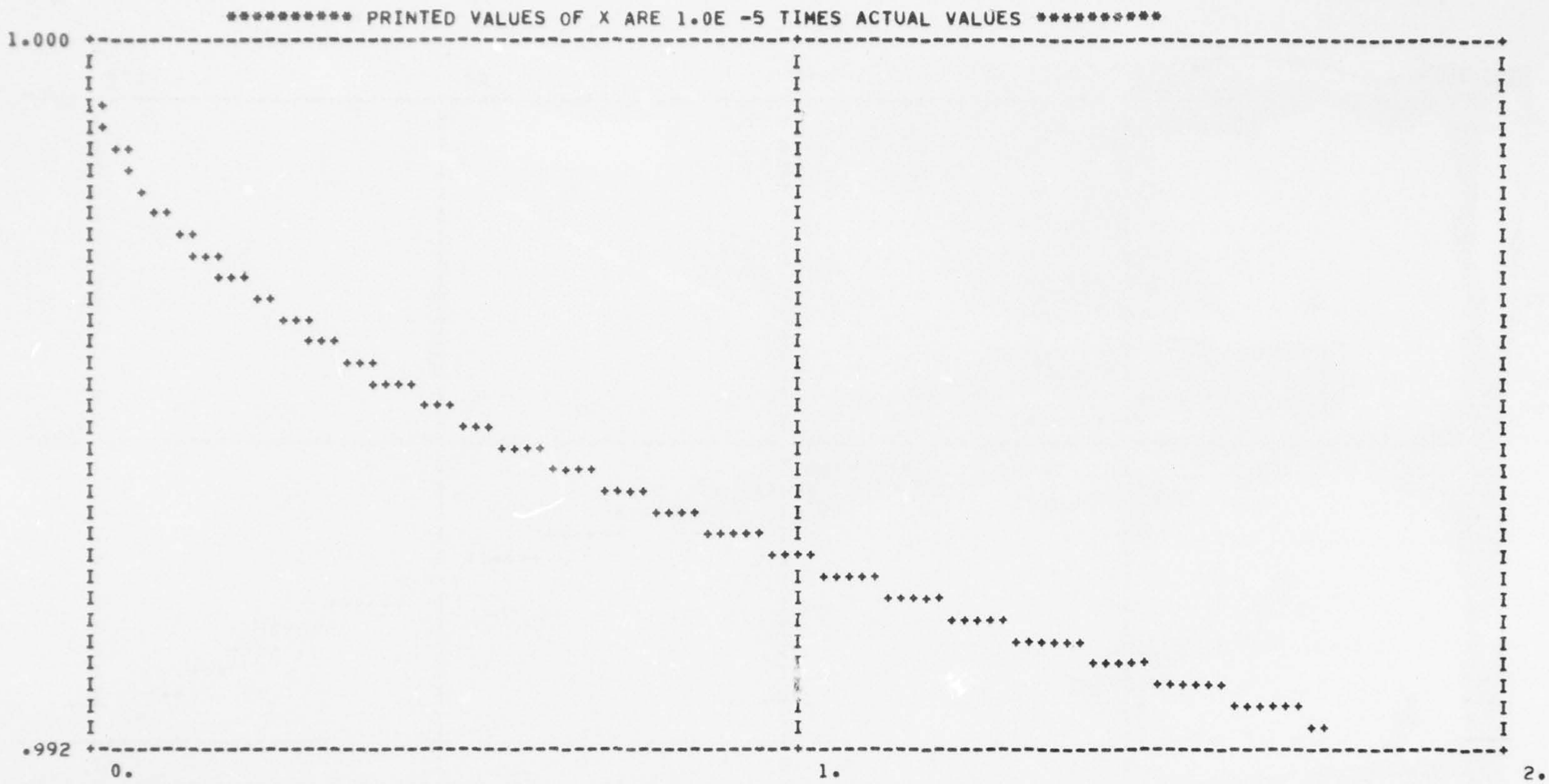
OPERATION TIME:

HOURS PER DAY = 12.0
DAYS PER YEAR = 365.0

FAILURE CRITERIA:

1. 20. % LIGHT FAILURES CONSTITUTES SYSTEM FAILURE.
2. 2 CONSECTIVE LIGHT BAR FAILURES CONSTITUTES SYSTEM FAILURE
3. 30% LIGHT FAILURES IN A BAR CONSTITUTES LIGHT BAR FAILURE.

Figure D4 (cont'd).



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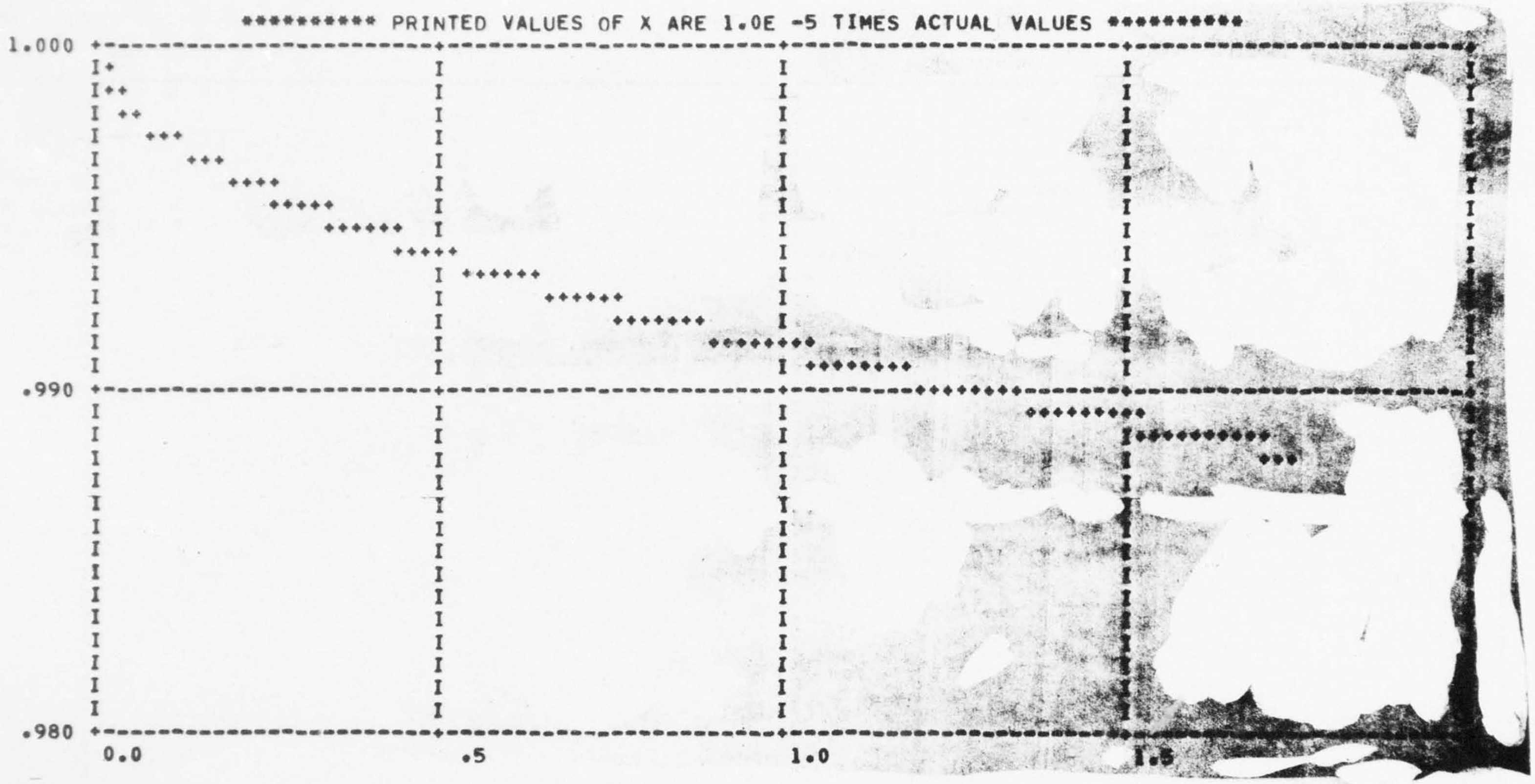
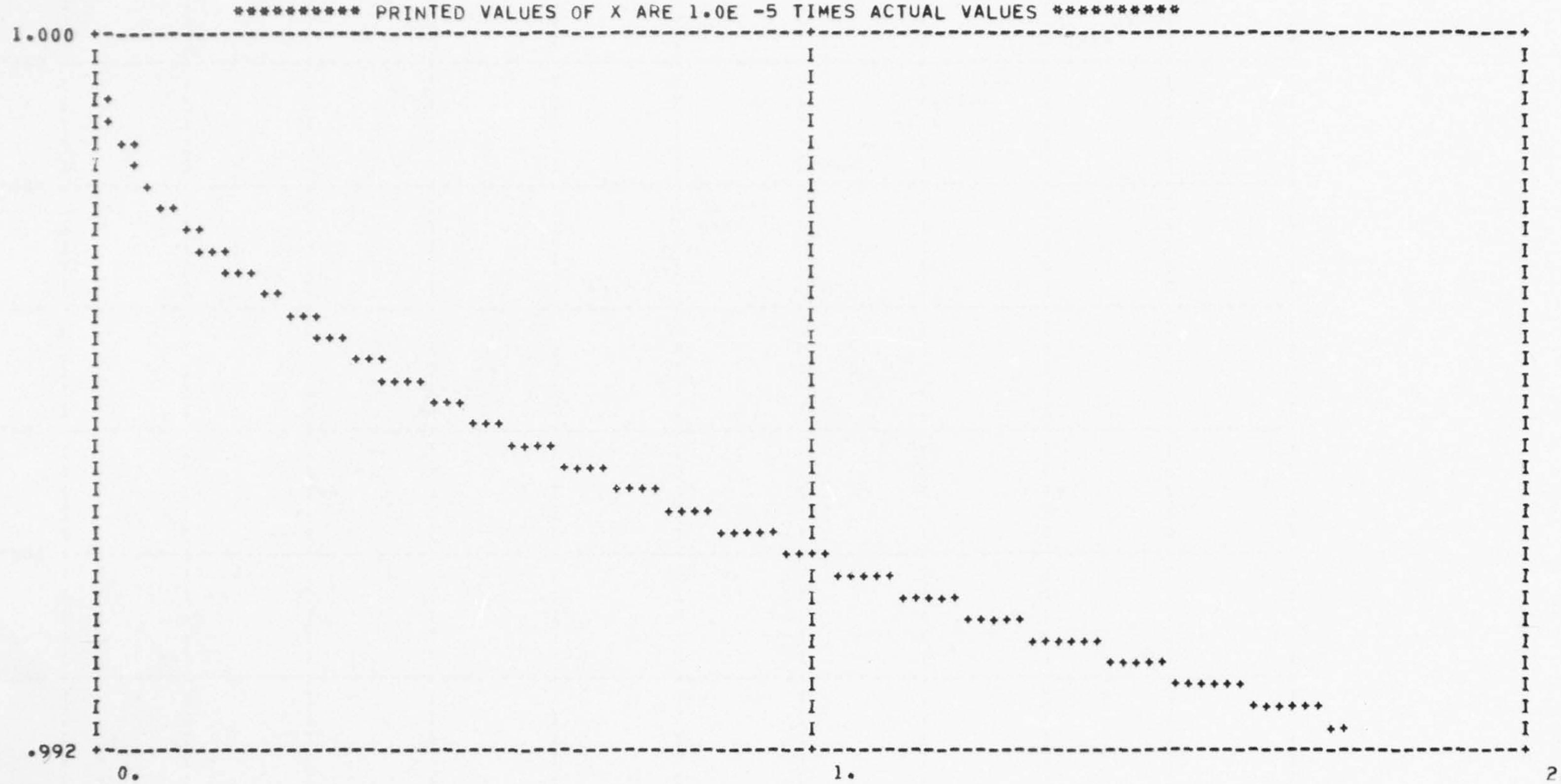
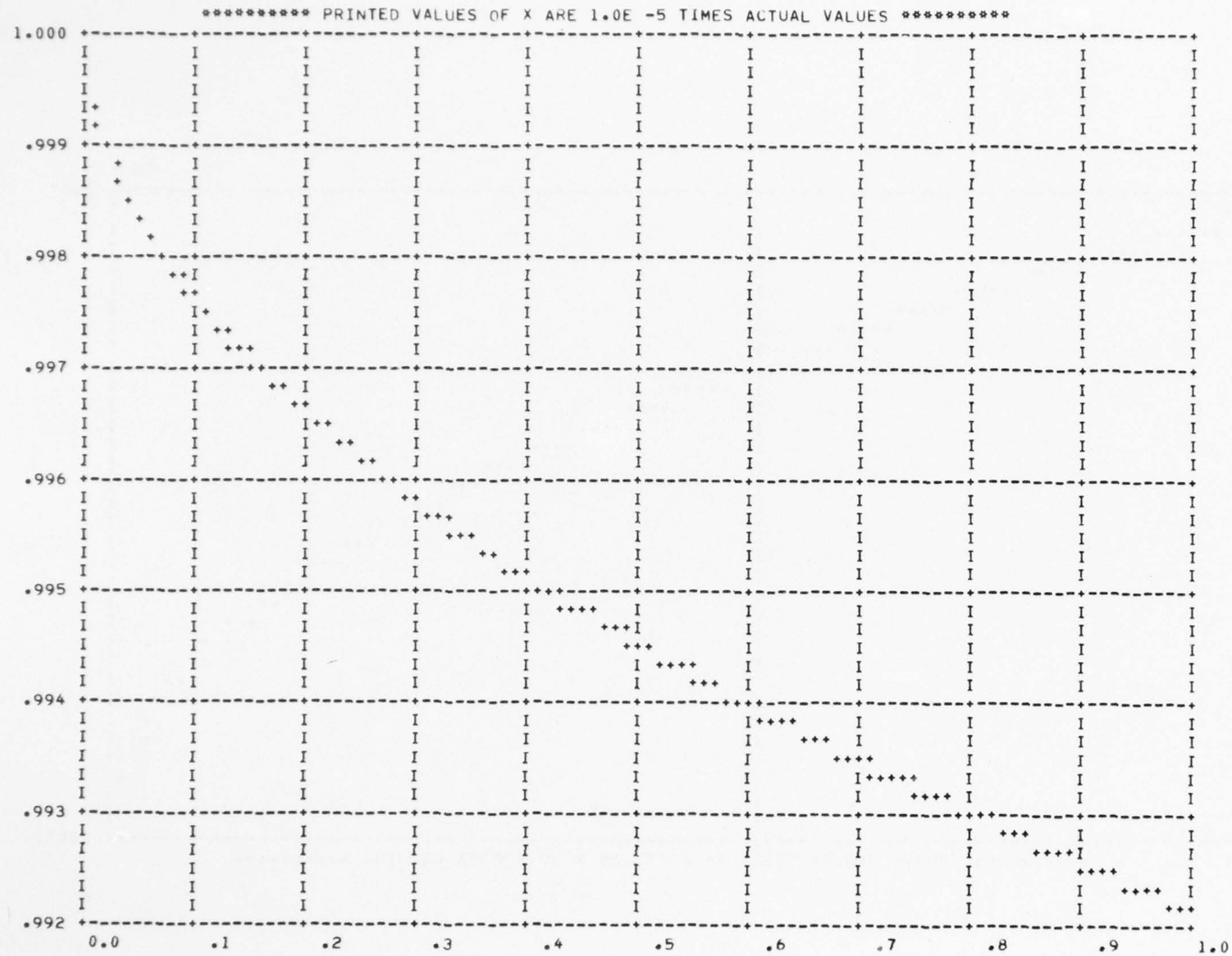


Figure D4 (cont'd).

********** PRINTED VALUES OF X ARE 1.0E -5 TIMES ACTUAL VALUES **********





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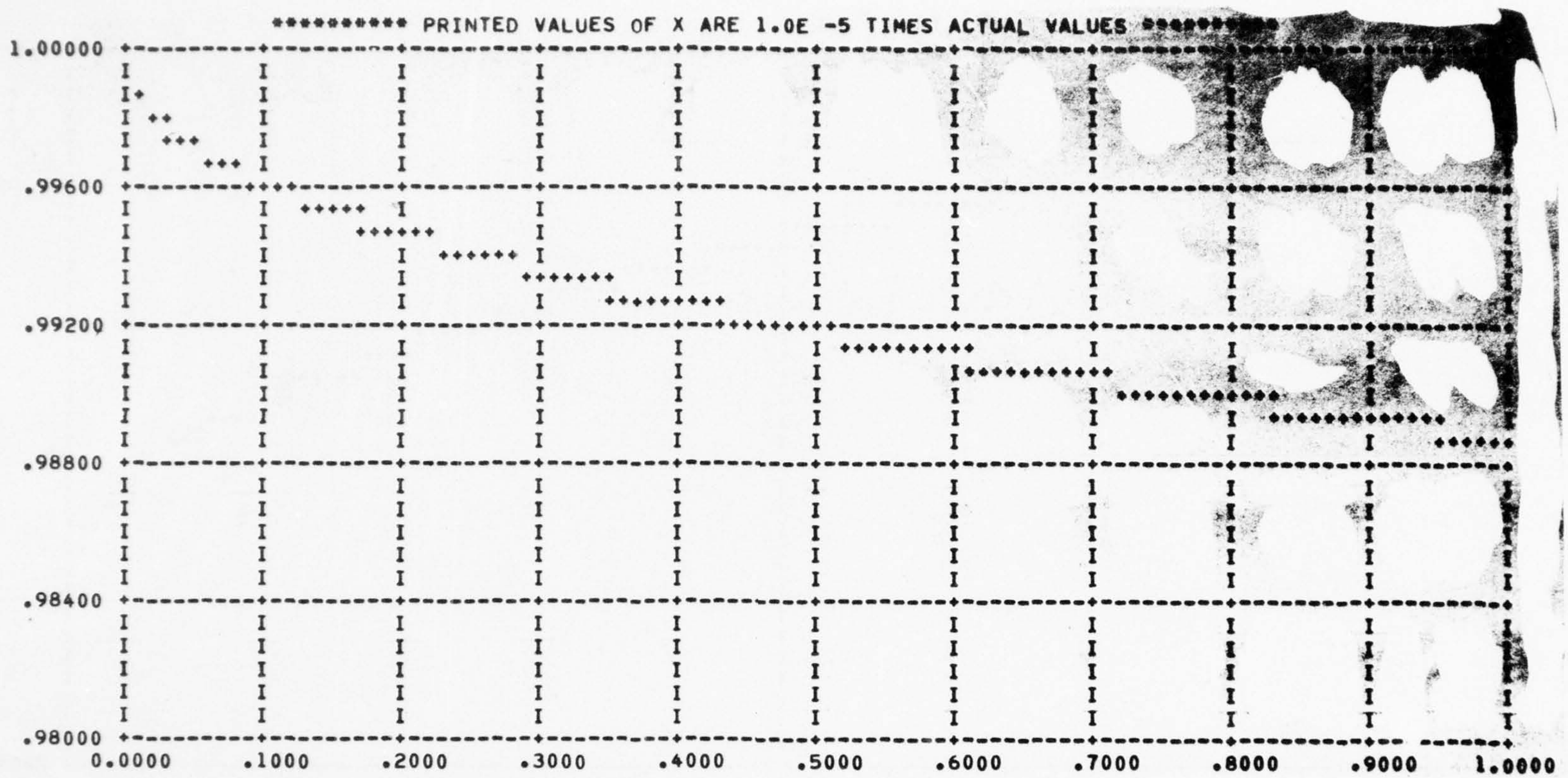

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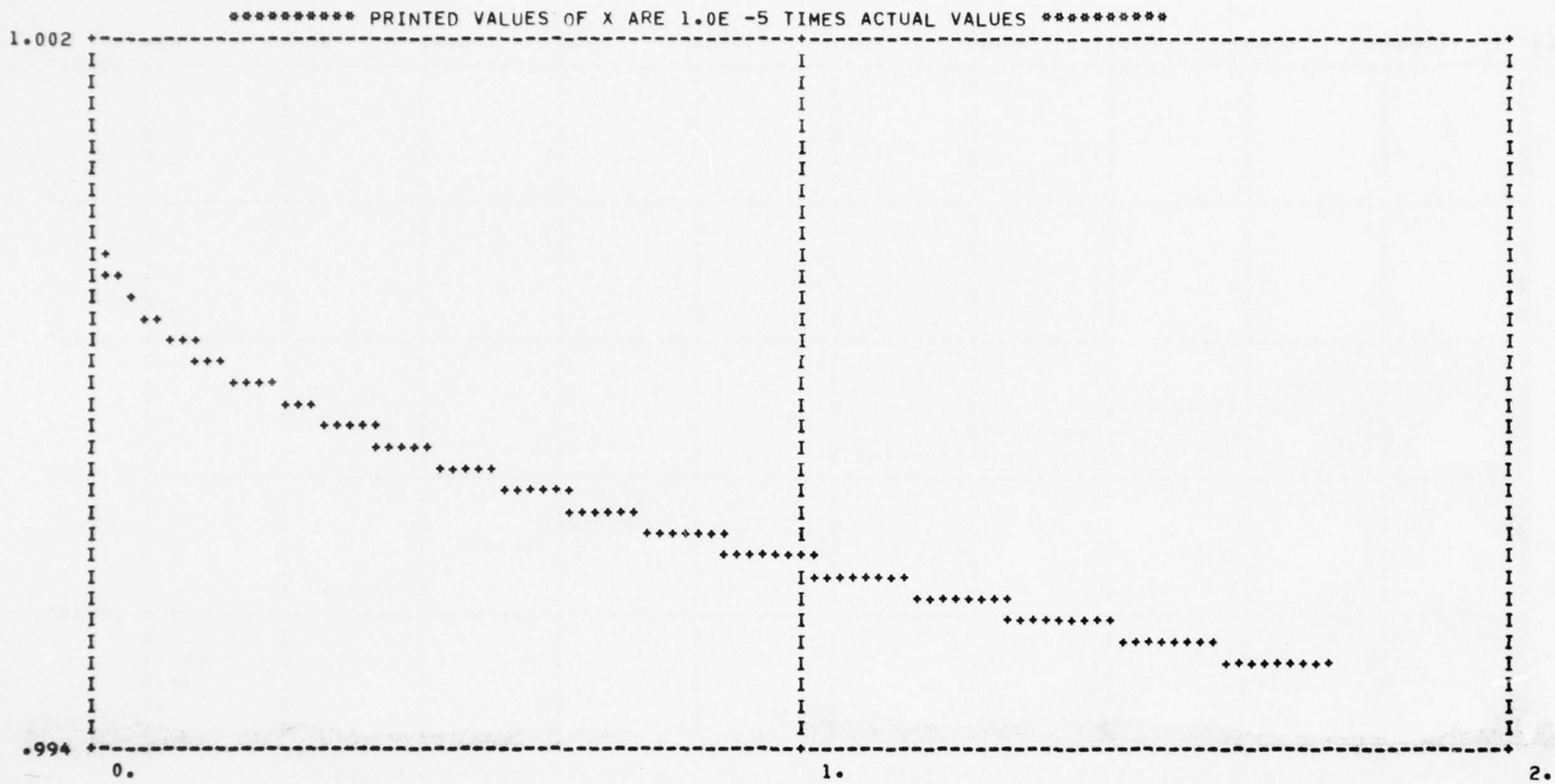

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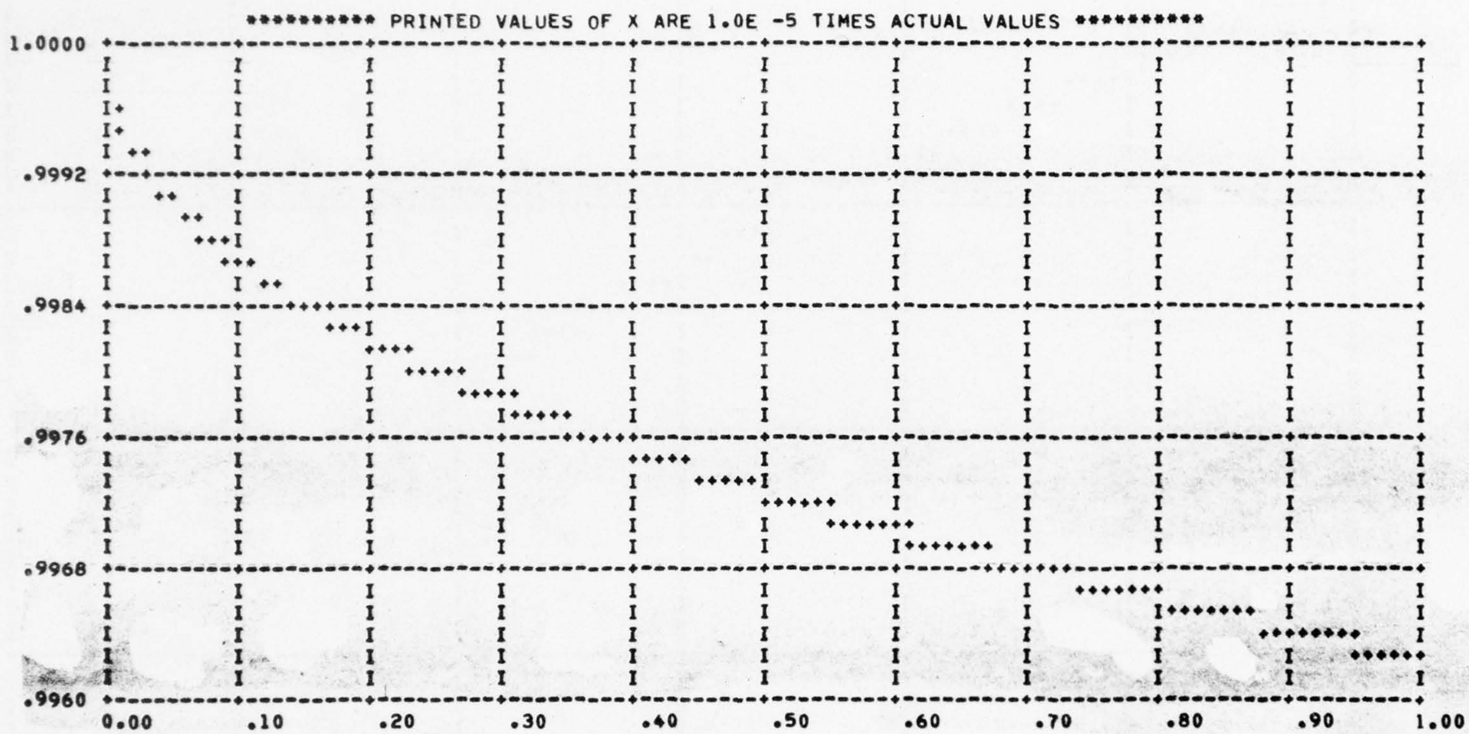

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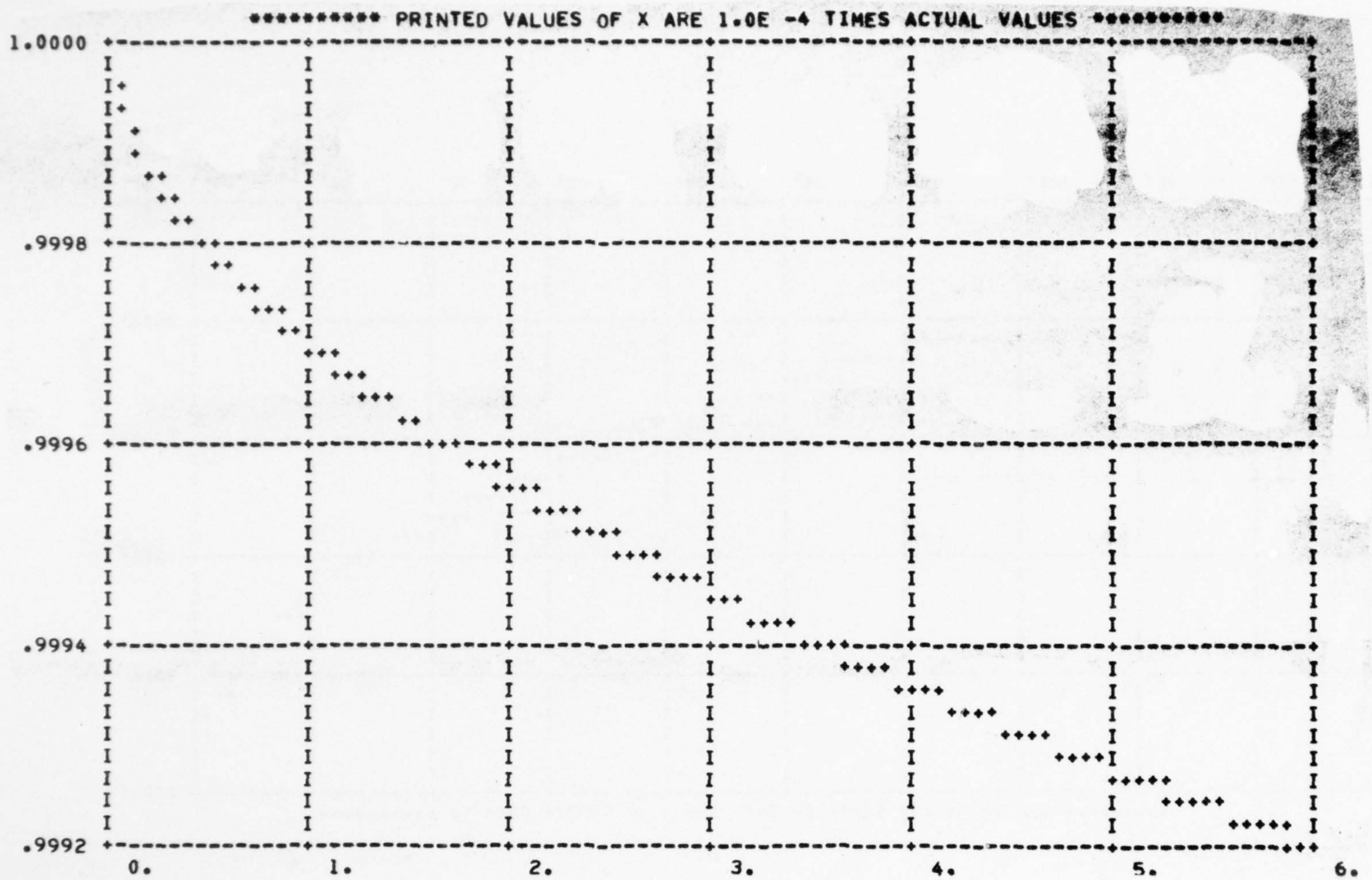

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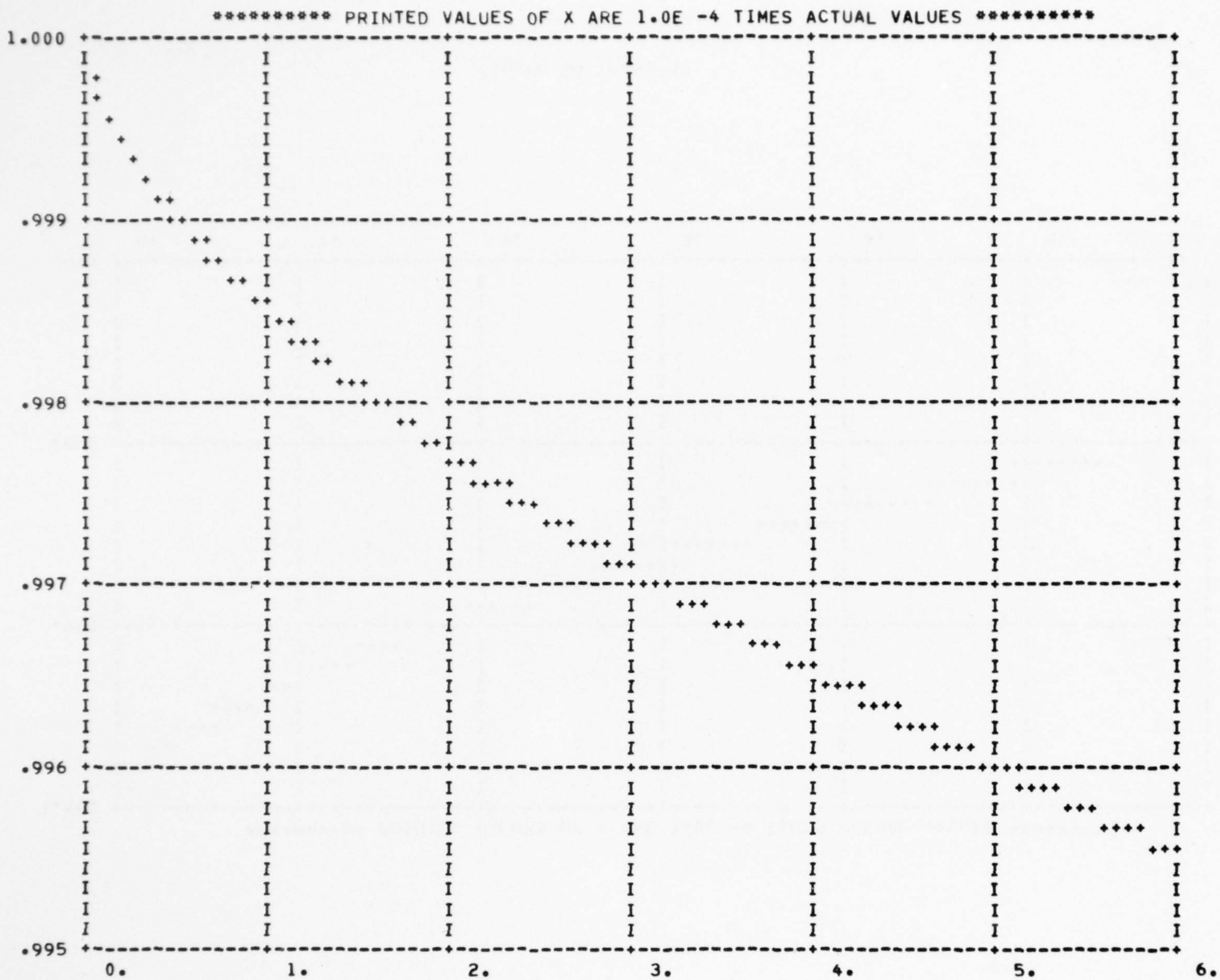

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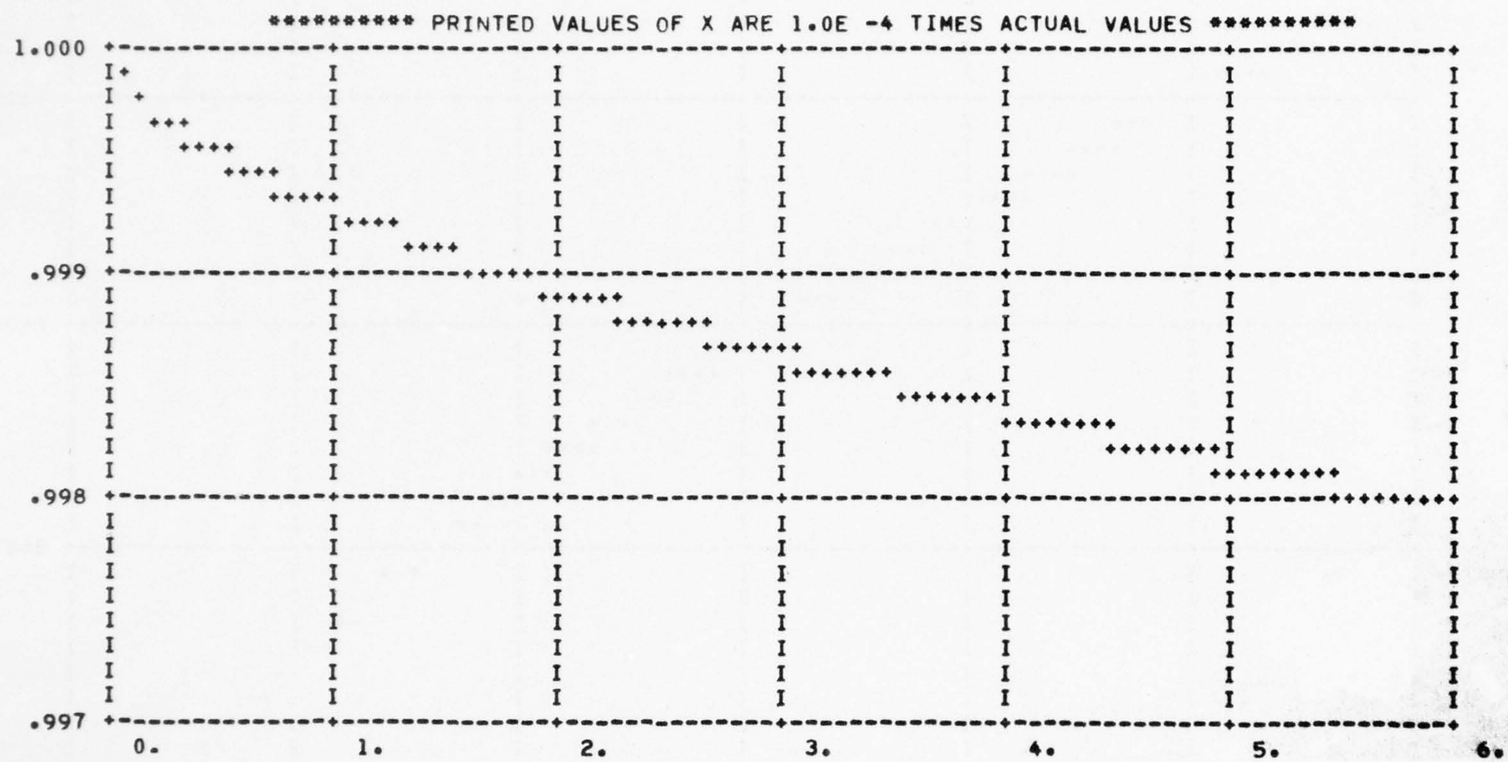

Figure D4 (cont'd).

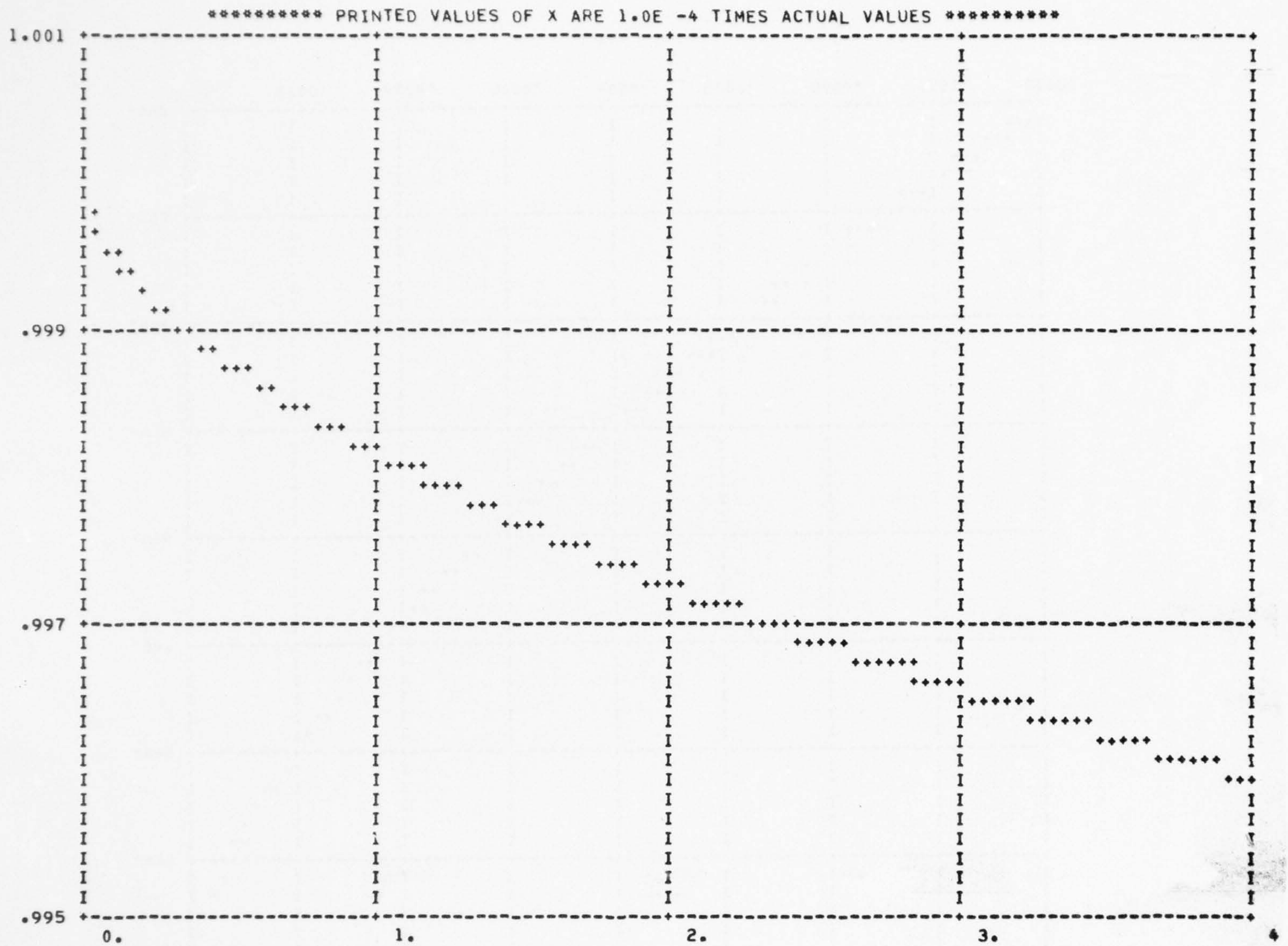

Figure D4 (cont'd).

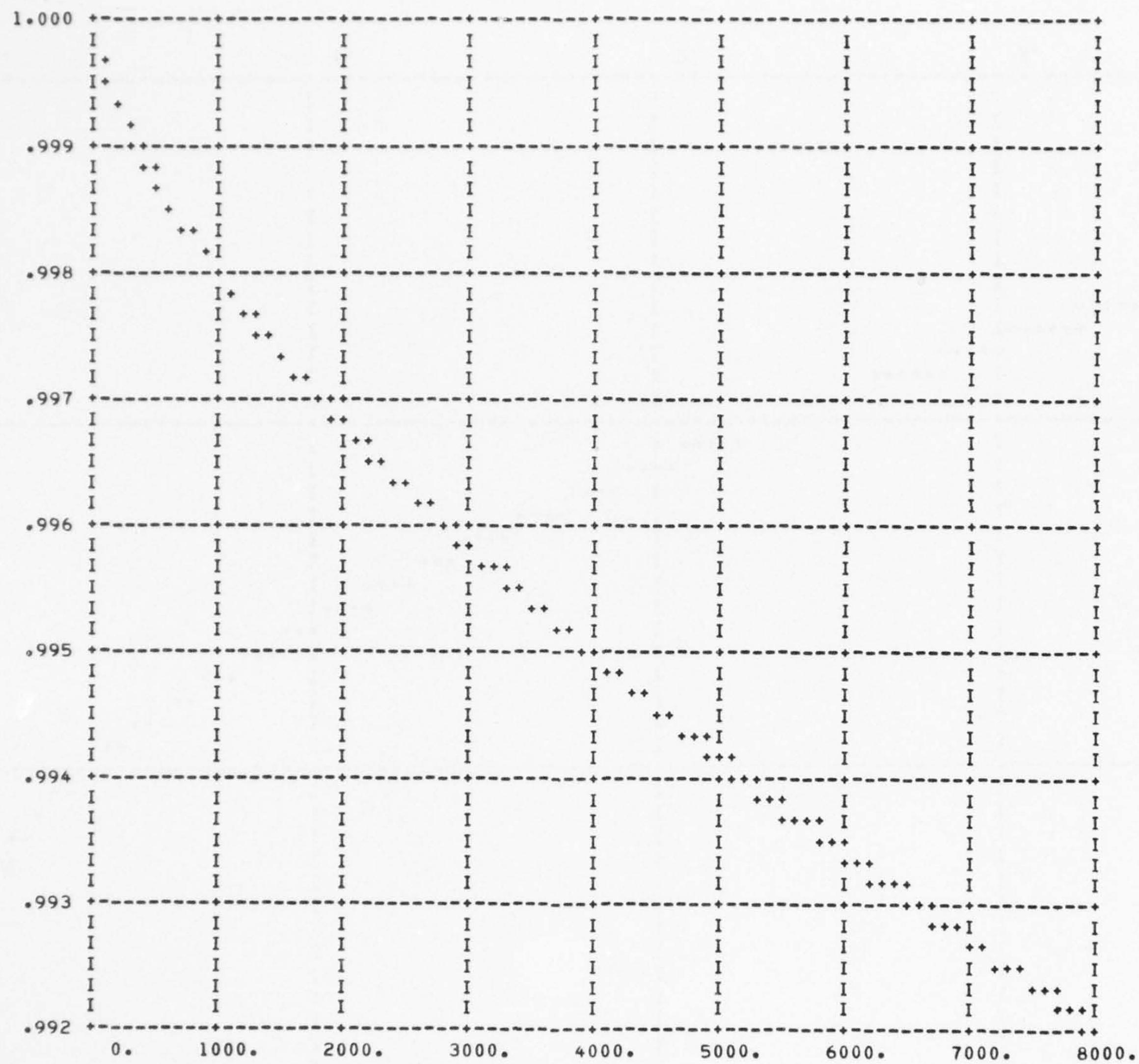

Figure D4 (cont'd).

ITERATION	MEAN UNIT REL	VAR UNIT REL	SYSTEM REL
1	.96636787	.00000719	.99679771
2	.96893124	.00000717	.99763923
3	.96776483	.00000656	.99727936
4	.96948571	.00000970	.99779753
5	.96633685	.00000655	.99678635
6	.96412021	.00000571	.99589691
7	.96773868	.00000608	.99727086
8	.96471664	.00000873	.99615183
9	.96288355	.00000581	.99532972
10	.96536844	.00000721	.99641709
11	.96642435	.00000724	.99681830
12	.96368437	.00000584	.99570305
13	.96015716	.00000542	.99388221
14	.96348752	.00000558	.99561336
15	.97101224	.00000771	.99819337
16	.96011214	.00000761	.99385590
17	.96040576	.00000666	.99402603
18	.96317831	.00000626	.99546975
19	.96764212	.00000736	.99723932
20	.95745191	.00000673	.99215189

BY INPUT DATA SET # 0 THE MEAN SYSTEM RELIABILITY IS .996015988
THE VARIANCE OF IT IS .000002442

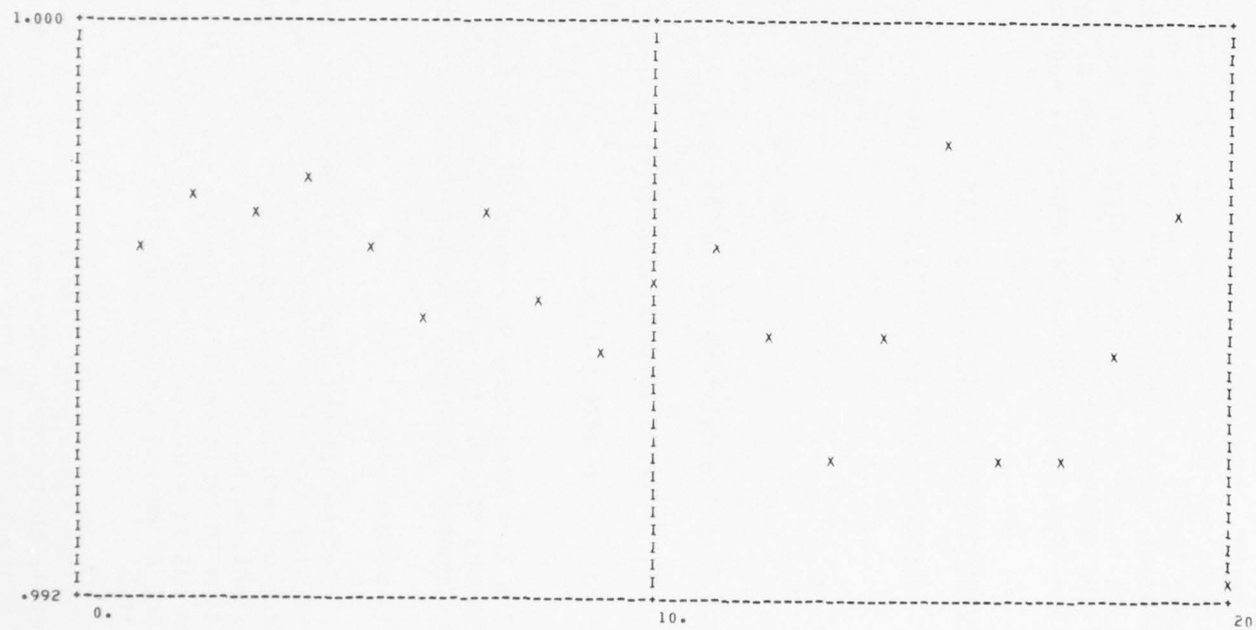

Figure D4 (cont'd).

APPENDIX E:

SENSITIVITY ANALYSIS

The analytical procedure used in the RAALS program combines individual analyses of the dependent variables as shown by the tree structure in Figure E1. Although the elements at a given level are listed separately, interactions tend to confound the individual elements' effects on the next higher level. This appendix presents a sensitivity analysis aimed at isolating the dependent variables' effects at three levels: the component reliability, the unit reliability, and the system reliability. The discussion centers on the physical effects of varying the individual elements rather than solely on the mathematical repercussions.

Component Reliability Sensitivity

The component reliability function was defined in Appendix B as

$$R_c = e^{\frac{-(t-t_s)^{c_m}}{c_f}} \qquad \text{[Eq E1]}$$

where C_m = the maintenance coefficient

C_f = the failure coefficient

t_s = the safety time.

In the tree structure in Figure E1, the four elements directly affecting component reliability are: replacement time, safety time, maintenance, and component failures. These elements are discussed below.

Replacement Time

The replacement time is defined as the period of time during which a particular component is expected to be in service. Figure E2 shows the effect of reducing lamp replacement time while holding other variables constant, using typical characteristics for a lamp component (Table E1). As time to replacement decreases, the reliability curve retains the same form but is truncated earlier. In a steady-state system, the overall effect of decreasing replacement time is to improve the component's reliability.

Since replacement time is a function of maintenance policy, it can be directly controlled. However, when the maintenance policy is established, the costs incurred by replacing components prior to their design life must be weighed against the resulting improvement in system reliability.

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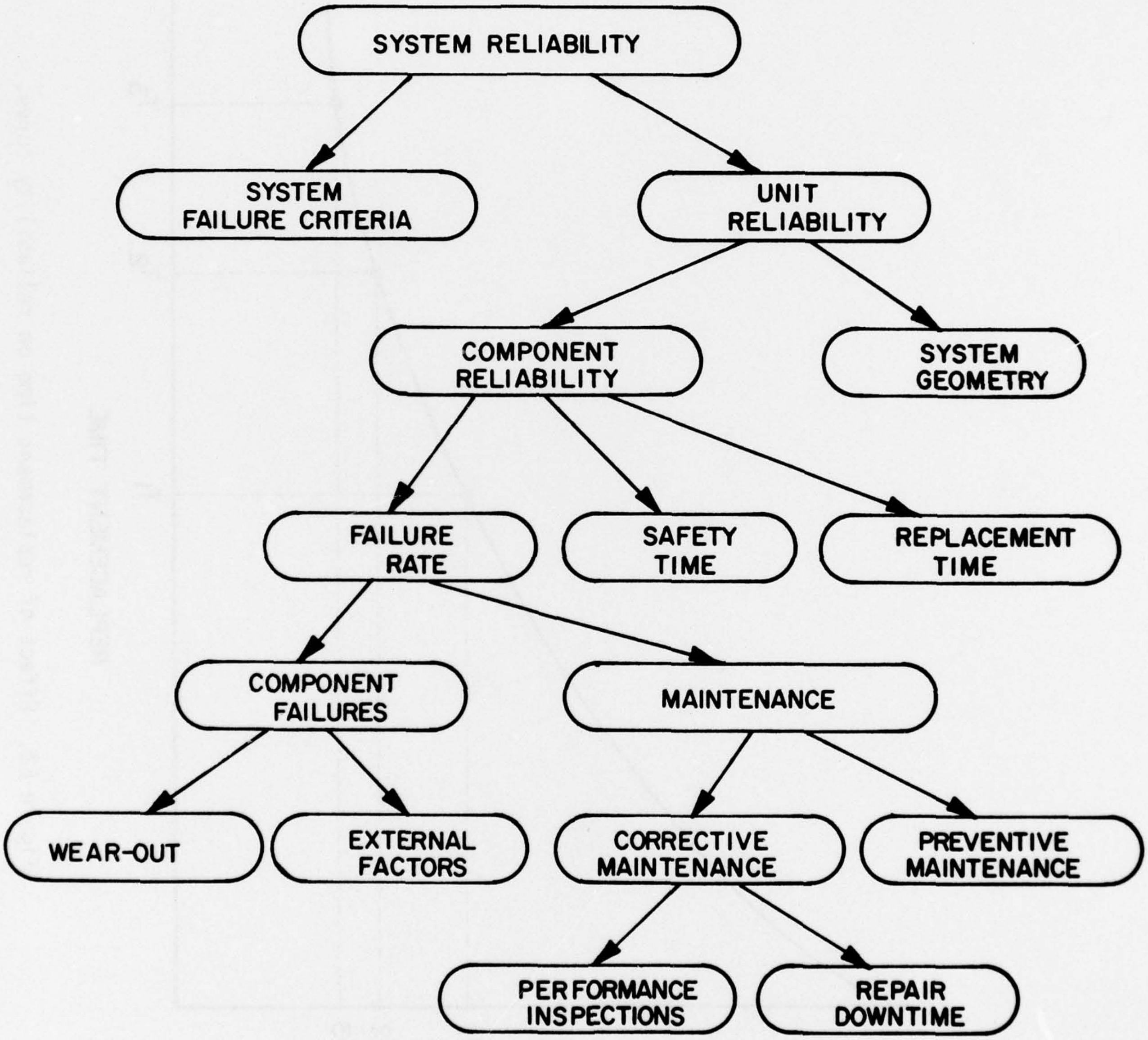

Figure E1. Tree structure of reliability analysis.

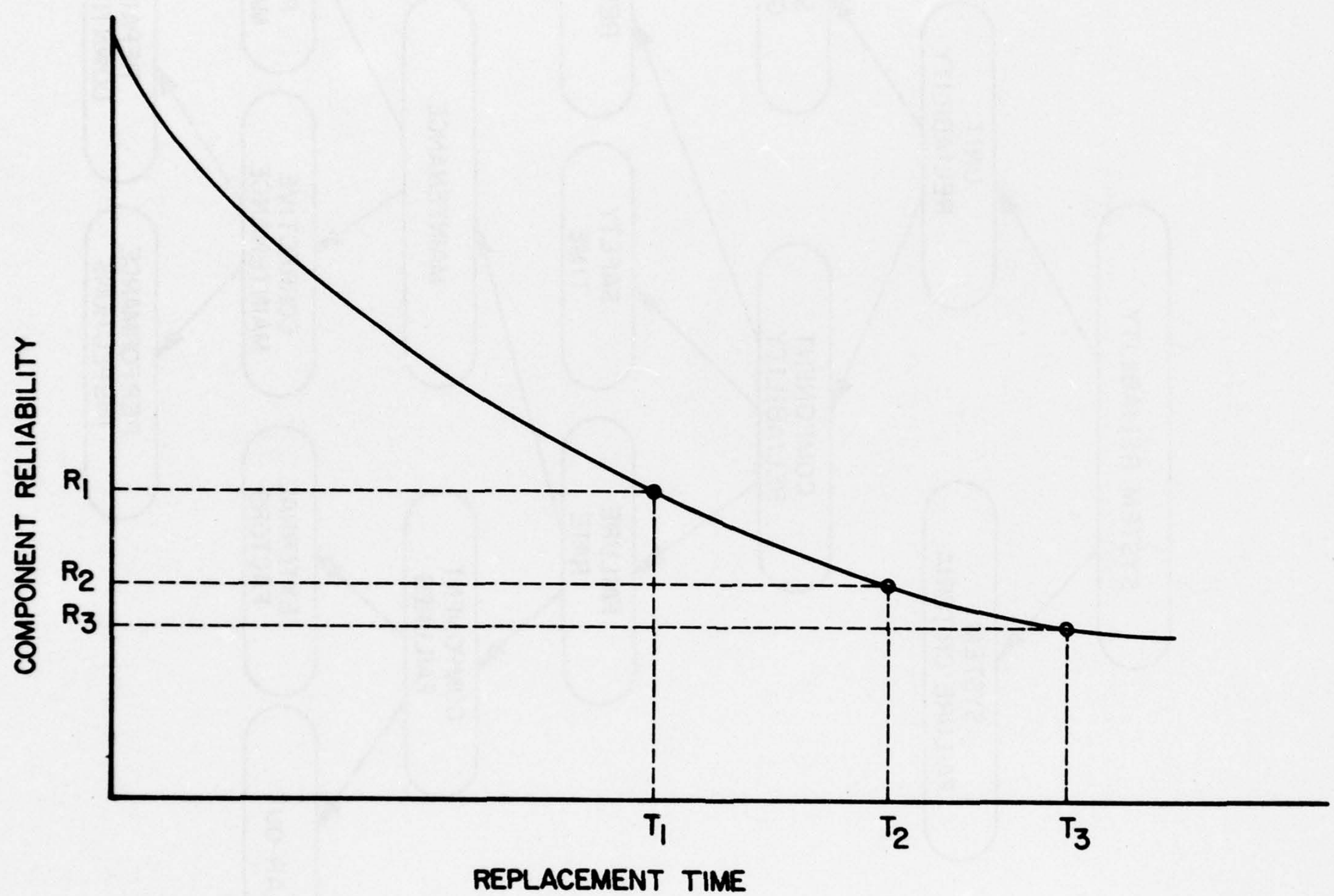

Figure E2. Effect of replacement time on reliability curve.

Table E1

Typical Lamp Characteristics

Component Type	Number	Failures Per Year	Replacement Time (Hrs)	Safety Time (Hrs)	Down-time (Hrs)	Design Life (Hrs)	Maintenance Coefficient	Failure Coefficient
Lamp 1	150	150	4000	0	12	4000	.647456	50,000
Lamp 2	150	150	3000	0	12	4000	.647456	50,000
Lamp 3	150	150	2000	0	12	4000	.647456	50,000

Safety Time

The safety time for a component is the period following installation during which the possibility of failure is zero or the reliability is 1.0. Figure E3 shows the effect of safety time on the component reliability curve. These curves were generated using the standard set of data in Table E1 and varying the safety time. The net effect of increasing safety time is to improve the reliability of the steady-state component. Because safety time is an attribute of the individual equipment item's design and manufacture, it cannot be controlled except through equipment selection.

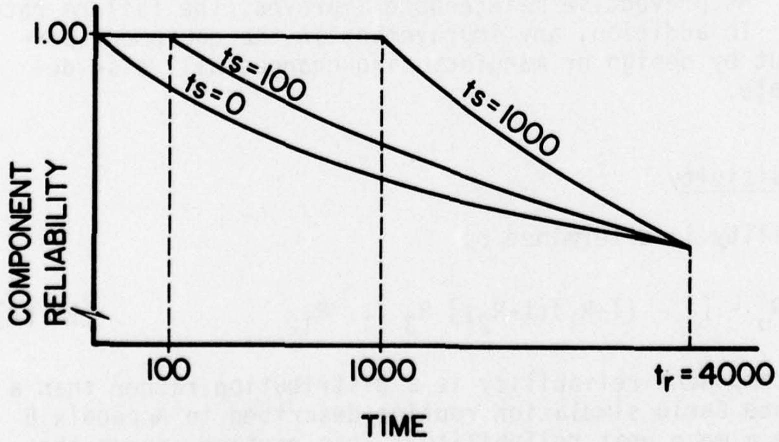

Figure E3. Effect of safety time on reliability curve.

Maintenance

Maintenance, which includes both corrective and preventive maintenance activities, is accounted for in the reliability function by a maintenance coefficient (see Appendix B, *The Maintenance Coefficient* section).

As shown in Figure E4, the maintenance coefficient increases exponentially with increasing downtime. From Eq E1, as the maintenance coefficient approaches 0, component reliability approaches 1, and as the maintenance coefficient approaches 1, the reliability approaches 0. Thus, the component reliability decreases with increasing downtime. Figure E5 illustrates the effect of decreasing the maintenance coefficient on the shape of the component reliability curve.

Downtime is principally controlled by the frequency of performance checks and the length of time required to make repairs or replacement. Thus, comprehensive monitoring of a lighting system will reduce detection time, thereby decreasing downtime and increasing component reliability. Decreasing the length of time for repairs by increasing the maintenance staff, stocking replacement parts, improving maintenance skills, etc., will also increase component reliability.

Failure Rate

In the component reliability function, failure rate is accounted for by the failure coefficient. As the percent of yearly failures with respect to the total number of equipment items in the system increases, the failure coefficient decreases exponentially, as shown in Figure E6. From Eq 1, as the failure coefficient approaches 0, component reliability approaches 0, and as the failure coefficient increases, the reliability approaches 1.0. Figure E7 shows the effect of the failure rate on the shape of the component reliability curve.

Since the failure rate considers all causes for equipment becoming nonoperational, there is interaction between the failure rate and preventive maintenance. As preventive maintenance improves, the failure rate typically decreases. In addition, any improvement in the equipment performance brought about by design or manufacturing changes will also decrease the failure rate.

Unit Reliability Sensitivity

The unit reliability is determined by

$$R_u = [1 - (1-R_1)(1-R_2)]\ R_3 \ldots R_{12} \qquad \text{[Eq E2]}$$

However, since each component reliability is a distribution rather than a single point, the Monte Carlo simulation routine described in Appendix B was used to determine a mean unit reliability. This routine causes the unit reliability to be a function of the system geometry as well as the component reliabilities, as shown in Figure E1.

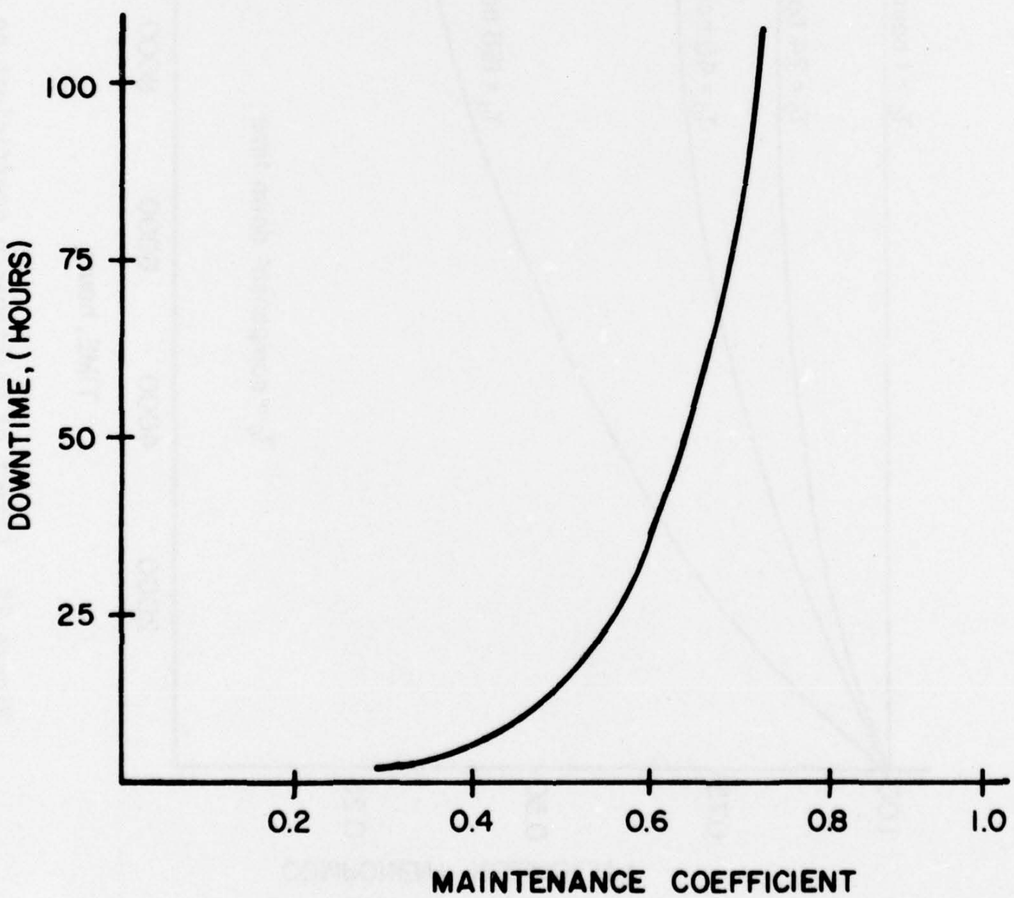

Figure E4. Maintenance coefficient vs. downtime.

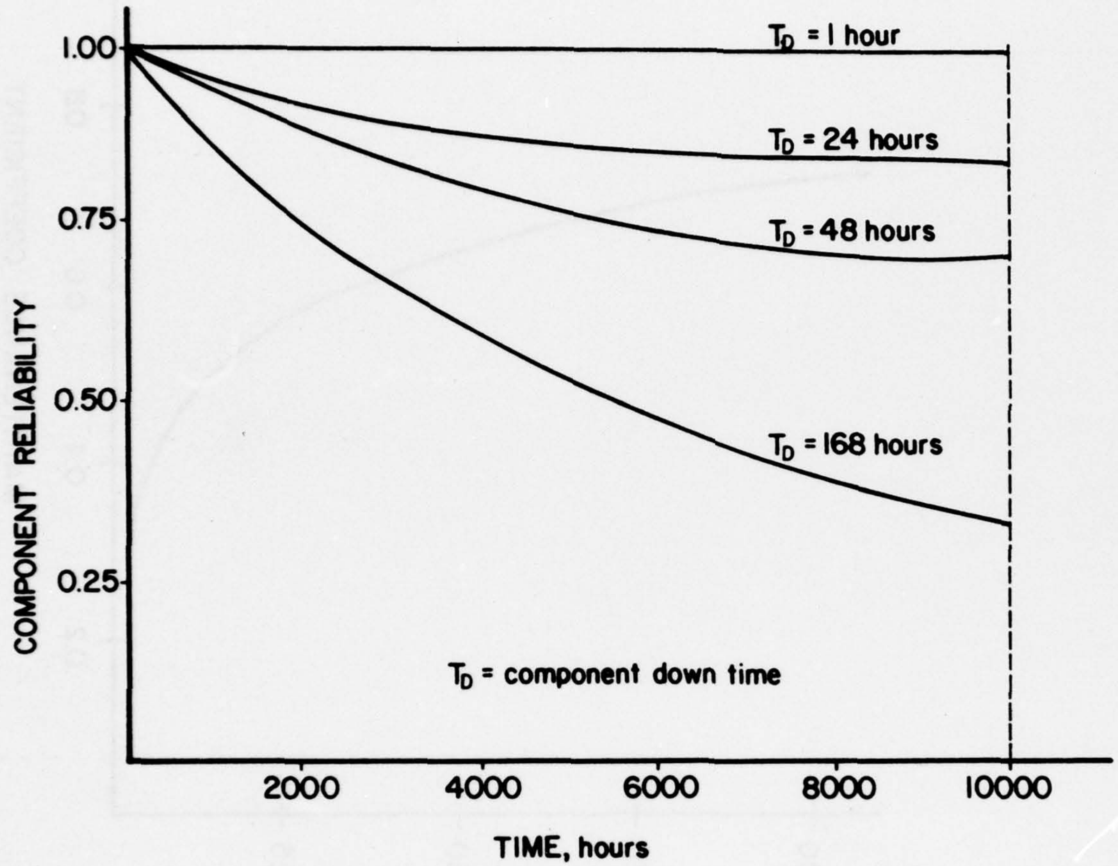

Figure E5. Effect of maintenance coefficient on reliability curve.

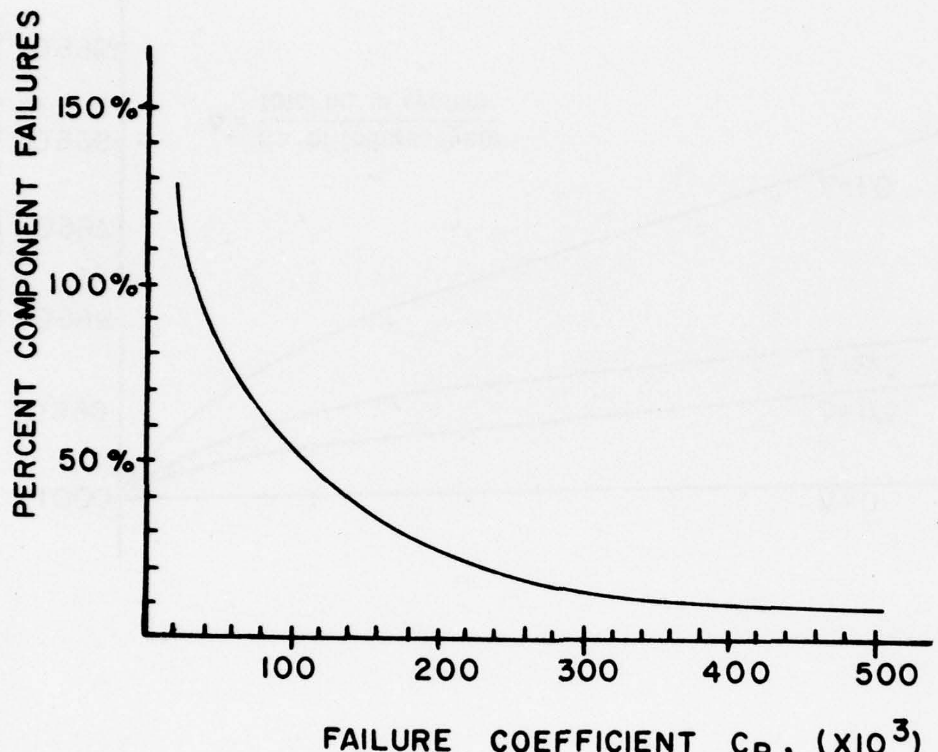

Figure E6. Failure coefficient vs. number of failures.

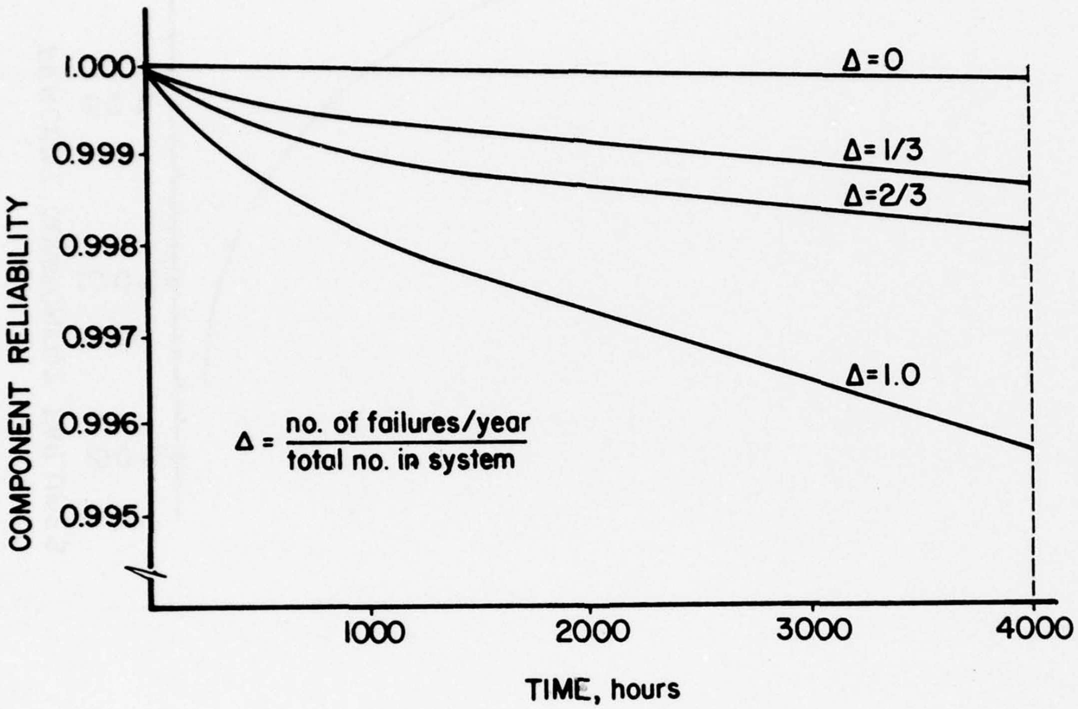

Figure E7. Effect of failure coefficient on reliability curve.

The geometry of existing systems is not a variable. However, the RAALS program can be used in designing new systems to evaluate the effect of the geometry (e.g., the number of primary cables in the system) on reliability.

Eq E2 indicates that improving the reliability of any one component improves the unit reliability. However, since unit reliability is the product of the individual component reliabilities, the unit reliability is influenced most by the weakest link in the system.

System Reliability Sensitivity

The system reliability is a function of the unit reliability and the system failure criteria, as discussed in Appendix B and expressed by

$$R_s = \sum_{i=o}^{n} W_i R_u^{n-i} (1-R_u)^i \qquad \text{[Eq E3]}$$

where R_u = the unit reliability

i = the number of outages in the system

n = the total number of lights in the system

W_i = the number of ways i outages can occur in the system without system failure (i.e., the failure criteria).

System Failure Criteria

The system failure criteria are subjective standards established to determine the minimum lighting requirements necessary to convey sufficient information to the pilot of an aircraft to maintain safe operations. In general, the failure criteria stipulate a percentage of random failures (NR) and a number of consecutive failures (NC).

Since the system failure criteria are based on an appraisal of the amount of information required by the pilot, the failure criteria are not a variable in the reliability analysis in the sense that they can be changed arbitrarily. However, if research indicates that the standards established for a type of system should be revised, the RAALS program can be used to estimate the resultant change in system reliability.

The effect of varying the failure criteria can be illustrated using three standard sets of data (Tables E2 through E4) for a runway centerline system. These data sets provide a range of unit reliability. Table E5 presents the resulting system reliability for the factorial analysis of the following failure criteria: random outages at 5, 10, and 20 percent, and consecutive outages at 2, 3, 4, and 5. The data are plotted on Figures E8, E9, and E10.

As anticipated, relaxing either of the failure criteria increases system reliability. For the medium and low R_u data sets, this increase is

Table E2

Low R_u Data Set ($\bar{R}_u$ = .95219226)

COMPONENT CHARACTERISTICS

COMPONENT TYPE	NUMBER	FAILURES PER YEAR	REPLACEMENT TIME (HRS.)	SAFETY TIME (HRS.)	DOWN TIME (HRS.)	DESIGN LIFE (HRS.)	MAINTENANCE COEFFICIENT	FAILURE COEFFICIENT
COMMERCIAL POWER	1	1	150000.	0.	1.	150000.	.216930	50000.
AUXILIARY POWER	1	1	150000.	0.	12.	150000.	.438409	50000.
CONTROL PANEL	1	1	150000.	0.	12.	150000.	.438409	50000.
CABLE TO VAULT	1	2	150000.	0.	12.	150000.	.438532	25000.
CONTROL VAULT	1	5	150000.	0.	24.	150000.	.501271	10000.
REGULATOR	3	6	150000.	0.	12.	150000.	.438532	25000.
PRIMARY CABLE	3	3	60000.	0.	24.	60000.	.544747	50000.
TRANSFORMER	150	15	40000.	0.	24.	40000.	.566801	500000.
SECONDARY CABLE	150	15	60000.	0.	24.	60000.	.544508	500000.
FIXTURE	150	15	40000.	0.	12.	40000.	.496796	500000.
LENSES	150	30	10000.	0.	24.	10000.	.659088	250000.
LAMP	150	250	4000.	0.	12.	4000.	.647577	30000.

OPERATION TIME:

HOURS PER DAY = 12.0
DAYS PER YEAR = 365.0

Table E3

Medium R_u Data Set ($\bar{R}_u$ = .956735198)

COMPONENT CHARACTERISTICS

COMPONENT TYPE	NUMBER	FAILURES PER YEAR	REPLACEMENT TIME (HRS.)	SAFETY TIME (HRS.)	DOWN TIME (HRS.)	DESIGN LIFE (HRS.)	MAINTENANCE COEFFICIENT	FAILURE COEFFICIENT
COMMERCIAL POWER	1	1	150000.	0.	1.	150000.	.216930	50000.
AUXILIARY POWER	1	1	150000.	0.	12.	150000.	.438409	50000.
CONTROL PANEL	1	1	150000.	0.	12.	150000.	.438409	50000.
CABLE TO VAULT	1	2	150000.	0.	12.	150000.	.438532	25000.
CONTROL VAULT	1	5	150000.	0.	24.	150000.	.501271	10000.
REGULATOR	3	3	150000.	0.	12.	150000.	.438409	50000.
PRIMARY CABLE	3	3	60000.	0.	24.	60000.	.544747	50000.
TRANSFORMER	150	15	40000.	0.	24.	40000.	.566801	500000.
SECONDARY CABLE	150	15	60000.	0.	24.	60000.	.544508	500000.
FIXTURE	150	15	40000.	0.	12.	40000.	.496796	500000.
LENSES	150	30	10000.	0.	24.	10000.	.659088	250000.
LAMP	150	150	4000.	0.	12.	4000.	.647456	50000.

OPERATION TIME:

HOURS PER DAY = 12.0
DAYS PER YEAR = 365.0

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Table E4

High R_u Data Set ($\overline{R}_u$ = .98724241)

COMPONENT CHARACTERISTICS

COMPONENT TYPE	NUMBER	FAILURES PER YEAR	REPLACEMENT TIME (HRS.)	SAFETY TIME (HRS.)	DOWN TIME (HRS.)	DESIGN LIFE (HRS.)	MAINTENANCE COEFFICIENT	FAILURE COEFFICIENT
COMMERCIAL POWER	1	1	150000.	0.	1.	150000.	.216930	50000.
AUXILIARY POWER	1	0	150000.	0.	12.	150000.	.000010	5000000.
CONTROL PANEL	1	0	150000.	0.	12.	150000.	.000010	5000000.
CABLE TO VAULT	1	0	150000.	0.	12.	150000.	.000010	5000000.
CONTROL VAULT	1	1	150000.	0.	24.	150000.	.500281	50000.
REGULATOR	3	1	150000.	0.	12.	150000.	.438328	150000.
PRIMARY CABLE	3	2	60000.	0.	24.	60000.	.544658	75000.
TRANSFORMER	150	3	40000.	0.	12.	40000.	.496785	2500000.
SECONDARY CABLE	150	4	60000.	0.	24.	60000.	.544488	1875000.
FIXTURE	150	5	40000.	0.	12.	40000.	.496787	1500000.
LENSES	150	17	10000.	0.	24.	10000.	.659060	441176.
LAMP	150	150	4000.	0.	12.	4000.	.647456	50000.

OPERATION TIME:

HOURS PER DAY = 12.0
DAYS PER YEAR = 365.0

Table E5

Failure Criteria Sensitivity

		NR					
		5%		10%		20%	
R_u	NC	R_s	v	R_s	v	R_s	v
LOW	2	.4883535	$.292\times10^{-1}$	.7185789	$.702\times10^{-2}$	.7193749	$.687\times10^{-2}$
	3	.5705402	$.346\times10^{-1}$	.9811285	$.831\times10^{-3}$	.9833767	$.681\times10^{-4}$
	4	.5728664	$.347\times10^{-1}$	.9927543	$.972\times10^{-4}$	.9991349	$.309\times10^{-6}$
	5	.5729187	$.347\times10^{-1}$	.9943739	$.464\times10^{-4}$	.9999544	$.1\times10^{-8}$
MEDIUM	2	.5661675	$.301\times10^{-1}$	.7574718	$.660\times10^{-2}$	.7578686	$.653\times10^{-2}$
	3	.6530299	$.329\times10^{-1}$	.9847144	$.921\times10^{-4}$	.9870361	$.474\times10^{-4}$
	4	.6554182	$.329\times10^{-1}$	.9966839	$.139\times10^{-4}$	.9993764	$.176\times10^{-6}$
	5	.6554708	$.329\times10^{-1}$	.9972400	$.115\times10^{-4}$	.9999696	$.1\times10^{-8}$
HIGH	2	.9751358	$.615\times10^{-4}$	.9753728	$.598\times10^{-4}$	.9758162	$.533\times10^{-4}$
	3	.9986546	$.964\times10^{-6}$	.9991312	$.754\times10^{-7}$	.9996754	$.21\times10^{-7}$
	4	.9989582	$.732\times10^{-6}$	.9998117	$.8\times10^{-8}$	.9999956	0
	5	.9989619	$.729\times10^{-6}$	.9999924	0	.9999999	0

NR = percent random failures allowed without system failure

NC = number consecutive failures allowed without system failure

R_u = unit reliability

R_s = system reliability

v = variance

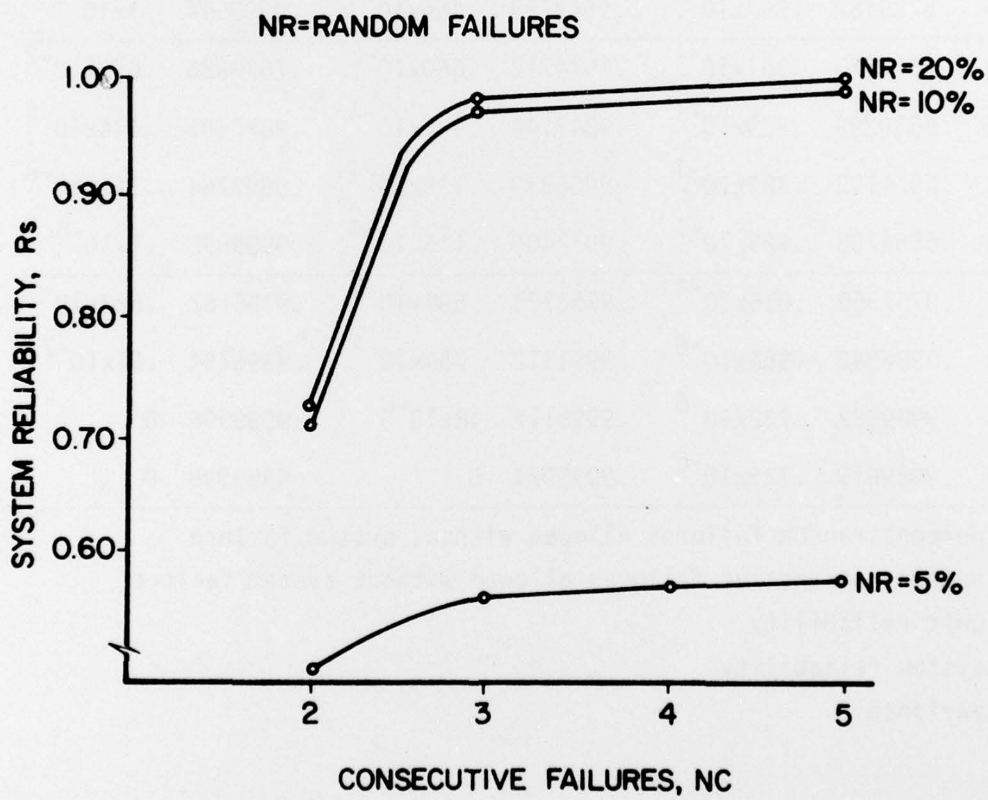

Figure E8. Reliability for low R_u data set.

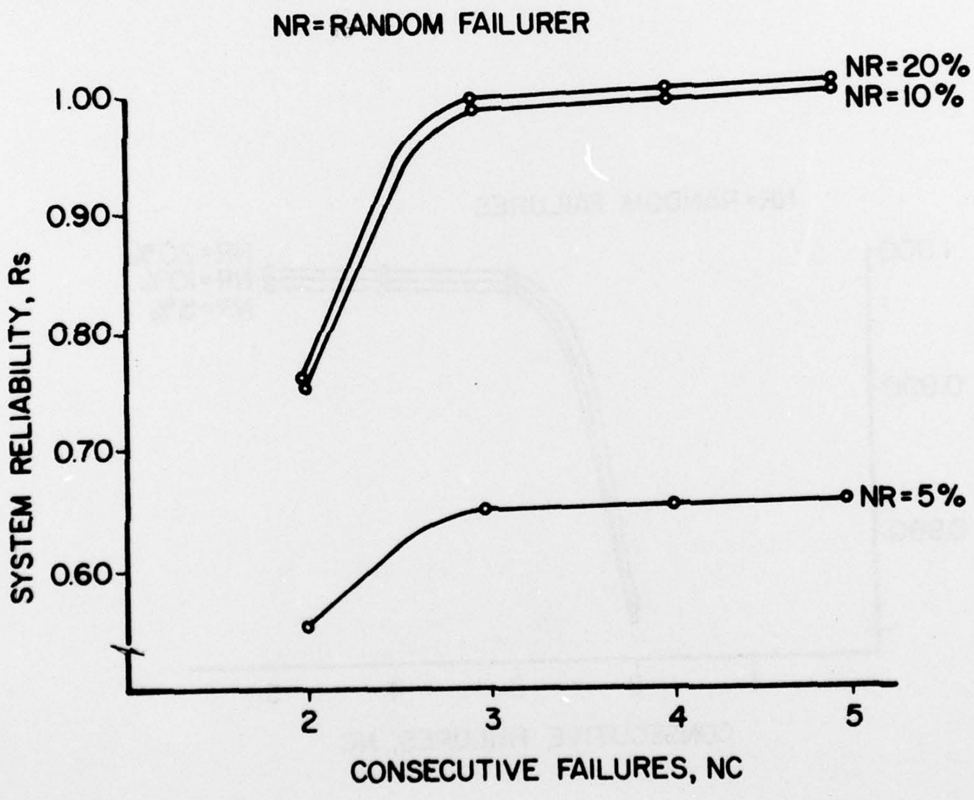

Figure E9. Reliability for medium R_u data set.

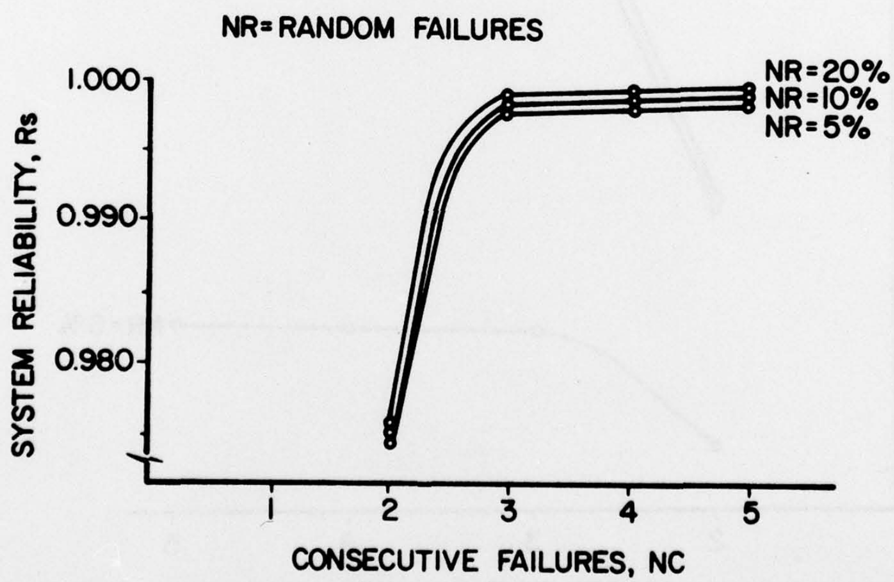

Figure E10. Reliability for high R_u data set.

quite large. However, for the high R_u data set, increasing NR has only a small effect on system reliability. In all cases, R_s increases significantly when NC is increased from 2 to 3. Further increases in NC produce only minor improvement in the system reliability.

Unit Reliability

The sensitivity of the system's reliability to changes in the unit reliability is also illustrated in Table E5. For failure criteria of NR equals 5 percent and NC equals 5, the system reliability increases from .5729187 for the low data set (R_u = .95219) to .9989619 for the high data set (R_u = .98724). Thus, an increase of .03505 in unit reliability produces an increase of .4260432 in system reliability. Figure E11 shows the relationship of R_s to R_u for these failure criteria. This exponential curve shows that the rate of change in R_s decreases rapidly as R_u approaches R_s.

Although system reliability has been shown to be sensitive to slight changes in unit reliability, the physical meaning is confounded by the multitude of variables which influence the unit reliability. Some of these variables can be controlled while others cannot. The following sections discuss the sensitivity of a sample of the controllable variables.

Replacement Time

The *Component Reliability Sensitivity* section of this appendix discussed the effect on the component reliability function of decreasing the replacement time. The resulting effect on system reliability can be demonstrated by decreasing the replacement time for the lamp and lens component.

Table E6 presents the relationship of system reliability and lamp replacement time using the data set from Table E3 and two sets of failure criteria: NR equals 20 percent, NC equals 4 and NR equals 10 percent, NC equals 3. The replacement times in this table are for group relampment at 70, 80, 90, and 100 percent of the lamp design life. As Table E6 shows, for the higher failure criteria, the system reliability is slightly improved as the lamp replacement time decreases. For the lower failure criteria, and thus lower system reliability, the effect of decreasing the lamp replacement time is more pronounced.

Table E7 presents the effect on system reliability of decreasing the lens replacement time by 50 percent* and varying the lamp replacement time from 70 to 100 percent of its design life. The same data and failure criteria were used as in Table E6. Again the impact of replacement time is more pronounced for the lower system reliabilities.

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*For the lens component, replacement time may be decreased by group restoration and cleansing of contaminants at some time prior to the design life.

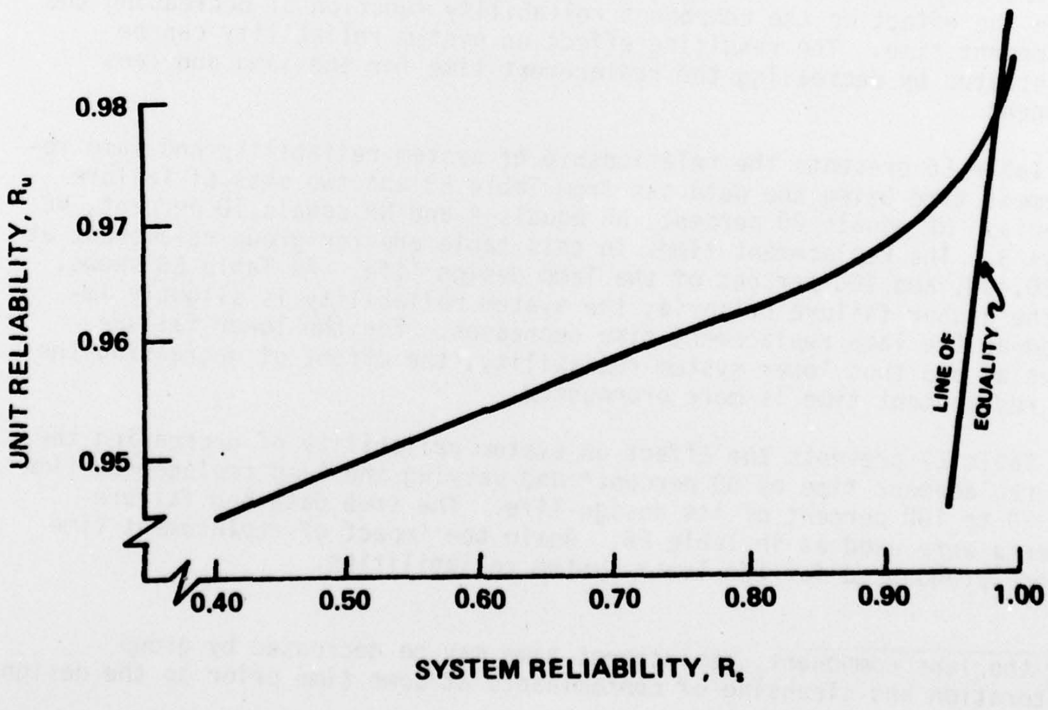


Figure E11. Relationship between system and unit reliability.

Table E6

Effect of Group Relampment

Lamp Replacement Time as % of Design Life	R_s With NR=20%, NC=4	R_s With NR=10%, NC=3
70	.99940	.98534
80	.99939	.98520
90	.99938	.98501
100	.99937	.98471

Table E7

Effect of Lens Restoration

Lamp Replacement Time as % of Design Life	Lens Replacement Time = 50% of Design Life	
	R_s With NR=20%, NC=4	R_s With NR=10%, NC=3
70	.99942	.98576
80	.99941	.98559
90	.99940	.98524
100	.99939	.98488

The combined effect of restoring lenses at one-half their design life and replacing lamps at 70 percent of their design life results in an increase in system reliability of 0.005 for the higher failure criteria and 0.105 for the lower failure criteria.

Maintenance

Airfield lighting systems are maintained systems; that is, to serve their intended function over a period to time, these systems require maintenance--both corrective and preventive. Consequently, the level of maintenance employed must be considered in evaluating the reliability of these systems. The effect of maintenance on an individual components's reliability function was previously discussed. This section focuses on the impact maintenance has on the system reliability.

Downtime is the principal measure of the level of corrective maintenance. As previously discussed, downtime is controlled by the frequency of performance checks and the length of time required to perform repairs or replacement. To illustrate the system reliability sensitivity to variations in downtime, several typical cases were analyzed. Table E8 presents the results.

For case 1, the standard data set of Table E3 with failure criteria of NR equals 20 percent, NC equals 4 was used for comparison.

Case 2 involved monitoring the entire lighting system for failures; the detection time thus becomes instantaneous, as illustrated in Figure E12. For critical component failures, where failure of the component is also system failure (e.g., commercial power, regulator, etc.), the remaining downtime is the time required to clear the system of operating aircraft. For other component failures (e.g., lamps, isolating transformers, etc.), the remaining downtime is the time to repair or replace the component. Using a conservative estimate of 20 percent reduction in downtime for all components, the improvement in system reliability due to monitoring would be 0.0282 percent.

Overall downtime can be reduced by increasing the maintenance staff, maintenance funds, and maintenance capabilities. Conversely, decreasing these elements increases downtime. Case 3 presents the system reliabilities resulting from varying the downtime for all components by ± 50 percent. Results illustrate that decreasing downtime results in an increase in R_S of 0.0603 percent while an equal increase in downtime decreases R_S by 0.8238 percent.

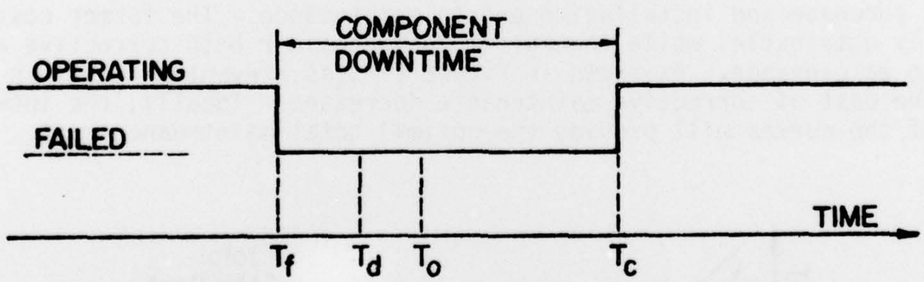
The first three cases varied the downtime of all components; case 4 illustrates the effect of varying a single component's downtime. If the lamps were visually checked and failures replaced each hour, 12 hours, or 24 hours, the resulting system reliabilities would be as shown in Table E8.

These examples are based on a system having a high reliability (99.9 + percent). For systems with lower reliabilities (e.g., 95 percent), the changes caused by varying the downtime are much more significant.

Table E8

Effect of Maintenance

Case	Change in Downtime	Reason for Change	R_s
1	0	Standard set of data	.999395
2	-20%, all components	System monitored	.999677
3	-50%, all components	Maintenance increased	.999980
	+50%, all components	Maintenance decreased	.991157
4	T_D (Lamp) = 1	Lamp replacement each hour	.999503
	T_D (Lamp) = 12	Lamp replacement every 12 hours	.999395
	T_D (Lamp) = 24	Lamp replacement every 24 hours	.999255



where T_f = time of failure

T_d = time of detection ($T_d \approx T_f$ when system monitored)

T_o = time system removed from service (T_o does not exist when component failure does not create system failure)

T_c = time failure is corrected.

Figure E12. Periods within component downtime.

Failure Rate

The effect of a component's failure rate on its reliability function was discussed previously. Table E9 shows the system reliability sensitivity to variations in failure rates for three components. These computations were based on the standard data set in the previous section. Fluctuations such as these can be attributed to:

a. An inferior shipment of a component

b. Atypical weather conditions (electrical storms for example)

c. Improving or relaxing the level of preventive maintenance

d. Design or manufacturing changes in the component production.

Summary

As described in this appendix, the reliability of a lighting system is sensitive to all of the elements shown in Figure E1. The magnitude of the sensitivity to each element varies with the interactions between the elements. However, the less reliable a system is, the more sensitive it will be to changes.

An overriding constraint to improvements in any system's reliability is cost. The cost of increasing reliability must be balanced with the costs resulting from not attaining the increase.

The costs associated with increasing reliability are attributable to equipment purchase and installation and to maintenance. The former costs are readily obtainable, while the latter must consider both corrective and preventive maintenance. As shown in Figure E13, as preventive costs increase, the cost of corrective maintenance decreases. Ideally, the intersection of the curves will provide the optimal total maintenance cost.

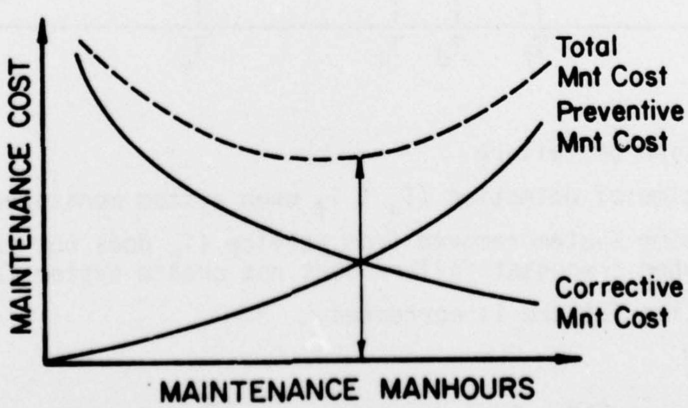


Figure E13. Corrective vs. preventive maintenance costs.

Table E9

Effect of Component Failure Rate

Component	Number of Failures/Year	R_s
Lamp	75	.999455
Lamp	150	.999395
Lamp	250	.999306
Isolating transformer	0	.999419
Isolating transformer	15	.999395
Isolating transformer	30	.999367
Regulator	0	.999507
Regulator	3	.999395
Regulator	9	.999103

In evaluating maintenance costs, the "cost of excess" should also be considered. It is possible to provide a system with a degree of freedom from failure far in excess of that which can be utilized. The cost of excess is then the cost associated with improving reliability beyond the minimum standards acceptable to the user.

The consequences of unreliability, or the costs associated with not attaining an acceptable reliability, are even more complex to analyze. They include:

a. Monetary costs incurred by the destruction of aircraft in accidents caused by lack of visual guidance.

b. Time loss incurred by passengers and airlines due to the inability to make scheduled arrivals or departures.

c. Injury incurred during accidents (or incidents) caused by lack of visual guidance.

d. Psychological effects incurred by pilots or airport managers who cancel scheduled operations because they feel that the lighting system will not provide the necessary information.

In formulating alternatives and recommending improvements or changes to a lighting system, all of the aforementioned costs must be considered. Previously, however, a quantified analysis of the independent variable--system reliability--was unavailable. As demonstrated in this appendix, the RAALS program can be used to evaluate the system reliability in light of the anticipated changes, thereby providing the decision maker with the information required to optimize system reliability.

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A/C 150/5340-19	*Taxiway Centerline Lighting System*
A/C 150/5340-21	*Airport Miscellaneous Lighting Visual Aids*
A/C 150/5340-24	*Runway and Taxiway Edge Lighting Systems*
A/C 150/5345-1E	*Approved Airport Lighting Equipment*
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